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Centralized multicasting AODV routing protocol optimized for intermittent cognitive radio ad hoc networks

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Abstract

The advancement of wireless technology is affected by Spectrum scarcity and the overcrowding of free spectrum. Cognitive Radio Ad Hoc Networks (CRAHNs) have emerged as a possible solution to both the scarcity and overcrowding challenges of the spectrum. The CRAHNs ensure that the Secondary Users (SUs) do co-exist with Primary Users (PUs) in a non-interfering manner. The SUs access the licensed spectrum opportunistically when they are idle. CRAHNs have many use cases which include intermittent networks here referred to as intermittent CRAHNs (ICRAHNs). For example, the Military (MCRAHNs). MCRAHN is complex and characterized by a dynamic topology which is subject to frequent partitioning and route breakages due to attacks and destruction in combat. This study optimises the routing protocols for intermittent networks such as the MCRAHNs. ICRAHN routing is a challenge due to the network's intermittent attribute, which is subject to destruction in the case of MCRAHN which is characterized by frequent link breakages. To better understand the routing in this network scenario, this paper presents two analytic models for the AODV and MAODV protocols based on queuing theory. The analytic models evaluate unicast and multicast AODV in terms of factors such as queuing delay, throughput, and network scalability. Numerical analysis indicates that MAODV outperforms AODV. Furthermore, the suggested routing protocols' performance was tested using network simulations utilizing the following metrics: throughput, Routing Path delay, Node Relay delay, and Spectrum Mobility delay. The simulation findings suggest that the MAODV protocol outperforms the AODV protocol.

Keywords: Cognitive Radio Ad Hoc Networks; Intermittent Networks; Primary Users; Secondary Users; Spectrum Scarcity

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1. Introduction

The emergence of the Fourth Industrial Revolution, the Internet of Things (IoT) and blockchain technologies which require a high-speed network (Internet) connectivity and spectrum have led to spectrum scarcity. Unfortunately, network connectivity depends on the availability of the spectrum and a stable network. To address these challenges of spectrum scarcity, the Federal Communication Commission (FCC) designed a framework which allows secondary users (SUs) to use the licensed spectrum opportunistically when not in use [1]. The military command chain depends on deployable and tactical communication capabilities to effectively coordinate and conduct operations from command posts in the face of several threats, such as terrorism, natural catastrophes and tensions along borders. When and where they are needed, their tactical communication solutions must be reliable and simple to deploy and redeploy. As the military transitions to a new, knowledge-based, network-centric force structure, bandwidth becomes more paramount. High bandwidth is beneficial to the user since it allows high-volume data interchange, fast response times, and high connectivity. To date, multicast networking support is becoming an increasingly important technology for both commercial and military distributed or group-based applications. Multicast routing protocols play a significant

role in ad hoc networks in facilitating communication. To enable group communication in these scenarios, several ad hoc routing protocols have been proposed. In transitioning from wired to wireless networking, protocol designers focused on designing multicast routing protocols that can cope with a mobile environment. Consequently, the main goal of most ad hoc multicast protocols is to build and maintain a multicast tree or mesh in a mobile environment, with a quick response to network changes so that packet loss is minimized. However, while most ad hoc multicast protocols have met this basic design goal, their performance has not been adequately examined under realistic scenarios. Routing in intermittent mobile networks is a challenge since there are no guaranteed routing paths. The nodes can be destroyed during the attack while they are relaying packets. This challenge has severe consequences in Intermittent Military Cognitive Radio Ad Hoc Networks (IMCRAHNs) nodes such as tankers and aircraft which can be destroyed in combat resulting in the partitioning of the network during a critical phase of the battle. In some cases, routing may be impossible. Longer delays in routing may be incurred resulting in packet timeout, increased packet drop rate, and the degradation of the performance of the network. The delays in IMCRAHNs caused by the destruction of nodes also increase the Routing Path (RP) delay, Spectrum Mobility (SM) delay, and Node Relay (NR) delay. The destruction of nodes, therefore, has a ripple effect on the IMCRAHNs. Furthermore, it also affects the achievable throughput as the packet drop rate increases.
The design of routing algorithms in IMCRAHNs requires a dynamic and robust technique that addresses the destruction of nodes and avoids incomplete paths while employing flexible and proactive recovery mechanisms. Several routing protocols exist which are designed to address the IMCRAHNs routing challenges. Unfortunately, current routing algorithms are not optimized for IMCRAHNs routing challenges such as delays. There is a need to optimize routing protocols for Delay Tolerant Networks (DTNs) such as the IMCRAHNs [2]. The routing protocols should reduce delays while improving achievable throughput. It is imperative to model these reactive ad hoc networking protocols analytically and then analyse them using simulation, particularly in tactical networks that assist military units in their operations. Furthermore, because military operations are complicated, careful planning and execution are essential to minimizing risks and potential losses and completing mission objectives within limited timeframes. Establishing the connection between the source and the destination typically involves two steps in AODV routing. Considering this, if the military communications networks suffer severe damage, it will be impossible to support tactical operations using civil communications by implementing international and commercial standards up to the network layer. In high mobility scenarios, however, AODV practically tends to perform better than other routing protocols. The AODV routing protocol's inability to quickly recover from lost connections is one of its drawbacks.

However, with the ever-evolving nature of tactical military networks as depicted in [3] there are still many open issues that need to be addressed to achieve the maximum benefit of the MANET. To design and deploy efficient and improved army tactical networking scenarios. Multicast is necessary for tactical military communication. A battle's outcome may depend on how well information is disseminated to the many war fighters involved [4]. The routing protocols in tactical MANETs need to efficiently support multicast traffic [5] The AODV protocol in the multicast setting subsequently becomes the multicast AODV (AODV).

This research considers both mathematical analysis and simulation analysis of the AODV and MAODV protocols with the following contributions to optimize and improve the protocols and subsequently enhance IMCRAHNs performance:
(i). Development of analytical models for the AODV and MAODV reactive routing protocols.
(ii). Comparison of the performance of the AODV and MAODV analytic models with regards to parameters such as queueing delay, number of nodes, throughput, spectrum availability
(iii). Analytical results are validated with simulation results wherein the protocols are simulated in three scenarios with 6, 35, and 70 nodes with the simulations being run for 100, 300, and 500 simulation seconds respectively.

The rest of the paper is structured as follows: Section 2 focuses on earlier but closely related efforts in terms of analytic and simulation works. The system model for the routing process using the AODV and MAODV protocols is presented in Section 3 using two analytic models. The analytic models depict the routing process using the AODV and MAODV protocols respectively. The evaluation of the AODV and MAODV is carried out in section 4 using two approaches, namely numerical analysis and simulation analysis using NS-2. Finally, the conclusion is presented in section 5.

2. Related work

Routing optimization is a well-known and established research topic with the fundamental goal of operating networks efficiently **[6]**. Realistically, a routing scenario occurs when two nodes need to exchange data. When this happens, handling the routing process requires the creation of a logical link among the involved elements, comprising of a set of required nodes **[7]**. The resulting routing must satisfy any application-specific constraints to be considered as a valid solution for the problem. A network route that connects more than two nodes at the same time is referred to as a multicast route. Multicast routing is mainly suited for a network scenario where resources need to be shared by multiple users. The use of unicast protocols for the creation of logical connections of elements of a group of users has proved to be ineffective.

Network resources (e.g. bandwidth) are likely to be wasted when copies of the same data are sent individually to each required node using the same network links. Solutions that optimize the network resources are thus much sought after. Numerous strategies, such as analytical and optimization, have been employed to achieve routing from both unicast and multicast perspectives. In this related work section, we consider the multicast technology to the routing problem within the context of AODV protocol.

2.1 Analytic Efforts

Recent research indicates that building scalable and effective routing algorithms for Mobile Ad Hoc Networks (MANETs) can be difficult due to constraints such as limited energy, node mobility, and changing network topologies **[8]**.

To achieve this, a great deal of concerted effort has been made to identify appropriate solutions. One such effort is the development of adaptive intelligent protocols, which can modify their routing strategy in response to the dynamic nature of MANETs given end-user requirements **[9]**.

In this section, we focus on these initiatives using the unicast AODV and MAODV. According to **[10]** the most used routing protocol in terms of MANETS is the Ad hoc On-Demand Distance Vector (AODV) routing protocol. However, the continually changing topology caused by node mobility makes MANET routing a difficult operation. Link failures and node failures in the network can result in the loss of network resources, making effective path selection between sender and receiver nodes critical for decreasing bandwidth utilization, consuming less energy, and improving Quality of Service (QoS). The authors in **[11]** focus on the importance of MANETS for defence applications specifically for countries like India which have boundaries and regions with large geographical diversity. The work recognises mobility as one of the defining features of MANET with a major impact on the performance of routing protocols. Subsequently, the efforts of the authors are directed at the performance of the AODV routing protocol characterised by numerous mobility scenarios including random movement-based, controlled movement-based and realistic mobility models. A rigorous mobility and scalability analysis of AODV is then considered concerning such routing parameters as transmission delay, number of received packets, control overhead, normalized routing overhead, packet delivery ratio and throughput as the performance measure using the Network simulator. In separate early survey efforts, the authors in **[12]** recognised the importance of a comparison between analytical and simulation results. This is a critical observation that has been recognized by a few researchers, as indicated by noticeably few or non-existent initiatives of this type. Many researchers tend to focus on simulation models as evidenced by the narrative in the next subsection (Simulation efforts).

2.2 Simulation Efforts

The routing paths in IMCRAHNs are nondeterministic which degrades the efficiency of routing protocols. Unfortunately, the existing routing protocols are not optimized for IMCRAHNs. We review schemes which were designed to mitigate the effects of SM, RP and NR delays in IMCRAHNs. It was observed that the IMCRAHNs delay is longer than the one for CRAHNs as a result, the IMCRAHNs are categorized as DTNs [13].

The mobility of nodes is also a challenge in ad hoc networks which negatively impacts the performance of routing algorithms. However, the location of nodes, the topology of the ad hoc network and the frequency of changes in the topology determine the routing approach. The design of routing algorithms is also complicated by the size of networks and transmission range. For example, Geo-routing (Geographic routing) is optimized for either geographical or zonal routing. In Geo-routing, packets are broadcasted towards the direction of the zone within which a destination node is likely to be encountered [14].

The Ad Hoc On-Demand Distance vector (AODV) routing algorithm is one of the common MANET routing algorithms [15]. The AODV is being considered for IMCRAHNs and its performance is encouraging. The reactive nature of AODV makes it more suitable for IMCRAHNs which is characterized by dynamic spectrum channel switching.

The Internet Protocol spectrum-aware geographic-based routing protocol (IPSAG) was proposed in [16]. The IPSAG is a geographical and spectrum-aware protocol which employs zonal routing using multicasting. IPSAG relies on prior knowledge of the spectrum and the geographical location of nodes for effective routing. For an effective relay of packets, all the nodes in IPSAG are expected to store the geographical locations of nodes in their neighbourhood or zone. In IPSAG, nodes employ the Greedy forwarding strategy to relay packets according to geographical location information. The nodes forward packets towards the direction of the destination node. The next hop node is expected to be closest to the destination and should have the best spectral quality. If a node has two options to relay packets, spectral density is used as a tiebreaker.

The performance of IPSAG was evaluated against the following routing protocols: The Spectrum Aware Routing for Cognitive Ad-hoc Networks (SEARCH) and the AODV. The results of IPSAG show that it is superior in terms of efficiency. IPSAG incorporates the Common Spectrum Opportunities technique which is used for routing decisions. A node with similar spectrum opportunities to the ones of the relay node is selected for data transmission to avoid channel switching costs [17] and the associated delays.

Though IPSAG was evaluated to be the best protocol, it is likely to drop many packets in intermittent networks with

no guaranteed routes. It is not designed to buffer packets until routes are re-established.
The functionality of AODV and its use of sequence numbers to maintain the freshness of routing paths is relevant to IMCRAHNs. It plays a fundamental role in route discovery. When a node receives a Route Request (RREQ), it compares its sequence number to the sequence number of the RREQ. The establishment of the routing path is based on the greater sequence number [18].
Multicasting AODV (MAODV) is a version of AODV, and it broadcasts packets to a given segment of the network [19]. However, MAODV does not perform well in repairing routes caused by breakages of relay nodes in IMCRAHNs. In the event of link breakages, the MAODV resumes transmission from the source node instead of continuing from the last relay node.

In WCETT, the best path is selected using the on-demand weighted cumulative expected metric [20]. The routing process is initiated by broadcasting the RREQ. The weighted cumulative transmission time is contained in the RREQ. The RERR is sent when the sequence number of the destination is equal to or less than the one in the route entry. When the RREQ is received, the decision to send an RREP is based on the cost of the RREQ. It should be less than the one of the previous RREQ which has the same sequence number. The paths with the lowest cost are selected. However, in [21]and [22], an alternative approach in the form of Graph-based Neural networks (GNN) is proposed. GNN can understand the complex relationship between topology, routing, and traffic in networks, and generalizes trained NN parameters over arbitrary topologies, routing schemes and variable traffic intensity. GNNs are thus leveraged in [23] to predict an optimal path between the source and destination. In [24] UAVs serve as relays in the communication between multiple IoT devices. The location and routing of UAV relays are to be jointly optimized using a GNN-based method to facilitate effective simultaneous data transmissions between multiple pairs of ground IoT devices.

3. System model

Our proposed system model depicts the routing/transfer of traffic packets from the source to the destination using two routing protocols. The routing protocols are the AODV and MAODV all belonging to the reactive class of routing protocols. Consequently, for the AODV and MAODV protocols, we provide two analytical models based on queuing theory.

3.1 AODV Analytic model

We consider the existence of a Mobile Ad Hoc Network described by an undirected graph G (N, E) as shown in Figure 1.
A set of mobile nodes $N = \{n_1, n_2, \dots \dots \dots \dots \dots n_m\}$ collectively constitute the MANET. The unidirectional/bidirectional links among the vertices are defined by the set of edges which are such that $E = \{e_1, e_2, \dots \dots \dots \dots . e_N\}$. Each of the nodes is equipped with Cognitive radio capabilities as in [25] [26].
Specifically, $E = \{(i,j) | e_i,\ v_j \in V\}$ a set of links $(i,j) \in E$ indicating nodes e_i and e_j are perceived to exhibit a queue length of N_{ij} in the informal network.
There are three parts to the allowable delay as follows:

- The transmission delay D_t;
- the Medium Access Delay based on the MAC access schemes used in each frequency band. The Switching Delay occurs when a node in a path switches from one frequency band to another [27] D_C;
- Queueing Delay based on the output transmission capacity of a node on a given frequency band D_Q

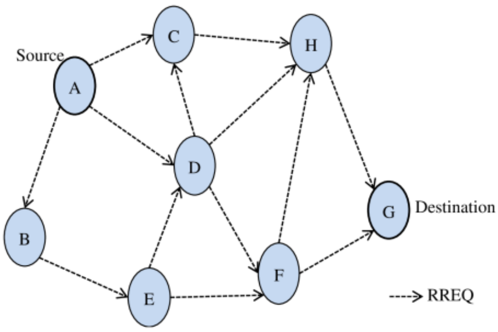

Figure 1: Network routing

$$D_{sum} = D_Q + D_C + D_t \quad [1]$$

Regarding the routing transmission of packets from the source to the destination, the symbol ρ_i is assigned to depict the ratio of the packet arrival rate φ_i and the packet service rate μ_i of MN [28]. When $\mu \leq \varphi$, we assume $P(m)$ the probability of having m packets queuing in the system ($m \leq K$. To this end, a packet arrives with rate ϕ and exits with rate μ.

$$P(m) = \frac{\emptyset}{\mu} \times \text{P(m-1)} = (\frac{\emptyset}{\mu})^m \times p(0) \quad [2]$$

The probability can further be transformed by using the relation $\sigma = \frac{\varphi}{\mu}$ and subsequently expressing the probability in eqn 2 as $p(m) = \sigma^m p(0)$.

Theorem A: The sum of the probability of happening of an event and not happening of an event is equal to 1. P(A) + P(A') = 1

Based on theorem A, the probability in eqn 2 can now be expressed as

$$P(m)=\begin{cases}\sigma^m x\frac{1-\sigma}{1-\sigma^{K+1}}, & if\ \sigma\neq 1\\ \frac{1}{K+1}, & if\ \sigma=1\end{cases} \quad [3]$$

The average number of packets Q_{AV} in the queue system can be expressed as:

$$Q_{AV}=\sum_{m=0}^{K} m\times p(m)$$

According to Little's law and the queuing theory, the sum of the queue time and the contention delay is the mean waiting time.

$$D_Q+D_C=\frac{Q_{AV}}{\sigma}$$

The sum of the delays can explicitly be expressed by equation 4 as:

$$D_Q+D_C=\begin{cases}\frac{\sigma}{1-\sigma}\frac{1-(K+1)\sigma^K+K\sigma^{K+1}}{1-\sigma^K}\frac{1}{\varphi}, & if\ \sigma\neq 1\\ \frac{K}{2\sigma}, & if\ \sigma=1\end{cases} \quad [4]$$

If we let $D_Q+D_C=D_{Upp}=\lim_{\sigma\to+\infty} D_Q+D_C$

$$D_{UPP}\approx\frac{K\times\sigma^{K+2}}{\sigma^{K+1}\times\sigma}$$

Definition I: The delay of a packet is the time it takes for the packet to reach its destination after it leaves the source. Assume $D^i_{\pi_n}(j)$ denotes the delay of packet j of s_0 -D_f pair i under policy π_n then the sample pair,

$$\overline{D^{\iota}_{\pi_n}}=\lim_{k\to\infty}\operatorname{supp}\frac{1}{k}\sum_{j=1}^{k} D^i_{\pi_n}(j)$$

The average delay overall s_0-D_f pairs for a particular realization of the network is then,

$$\overline{D^{\iota}_{fn}}=\frac{2}{n}\sum_{i=1}^{2/n} D^i_{\pi_n} \quad [5]$$

The delay for a scheme Π is the expectation of the average delay overall s_0-D_f,meaning the delay can now alternatively be expressed using equation 6 as:

$$D_{\pi(n)}=\mathrm{E}\left[\overline{D_{\pi_n}}\right]=\sum_{i=1}^{n/2}\mathrm{E}\left[\overline{D^{\iota}_{\pi_n}}\right] \quad [6]$$

Definition II (Throughput-delay optimality): A pair $(T(n),D(n))$ is said to be throughput-delay $(T-D)$ optimal if there exists a scheme π with $T_\pi(n)=\Theta(T(n))$ and $D_\pi(n)=\Theta(D(n))$ and with ∀ scheme π' with $T_{\pi'}(n)=\Omega(\mathrm{T}(n))$ and $D(\pi')(n)$=$\Omega(D(n))$.

3.2 MAODV Analytic Model

Multicast AODV protocol offers a quicker adaptation to complex network constraints, limited processing, and minimal network utilization. Multicast AODV protocol produces duplex direction distributed multicast trees that enable us to connect multicast sender and receivers. There are four messages in the multicast AODV routing protocol [29] as follows:

- Join-route: A node sends a query to join a specific group using the join-route.
- Route reply: Members of the group can send the response back to the soliciting node regarding the route available.
- Multicast activation: Used to form a multicast tree from which all the group members can connect and share information effectively.
- Group hello: The hello message will be used to keep track of the connectivity between group members.

Let $\boldsymbol{s_0}\in\boldsymbol{N}$ be a multicast source and $\boldsymbol{D_f}\subseteq\boldsymbol{N}-\{\boldsymbol{s_0}\}$ a set of destinations. A multicast tree $\boldsymbol{M}(\boldsymbol{s_0},\boldsymbol{D_f})\subseteq\boldsymbol{G}$ is rooted at $\boldsymbol{s_0}$ and reaches all destinations in $\boldsymbol{D_f}$. In general a routing path on M from $\boldsymbol{s_0}$ to a destination $\boldsymbol{nt_{path}}\in\boldsymbol{D_f}$, depicted as delay$\big(\boldsymbol{M}(\boldsymbol{s_0},\boldsymbol{v_t})\big)$ translates to a criteria for the routing protocol to find a multicast tree T*$(\boldsymbol{s_0},\boldsymbol{D_f})$ such that the delay is either less than or equal to the permitted delay **[30].** Furthermore, the multicast tree $\boldsymbol{M}$ has size $\boldsymbol{W}$ such that $\boldsymbol{W}=|\boldsymbol{M}|$.

Extending the AODV protocol, the total delay (D) experienced by the multicast packets when transmitted from a source node (s_0) to a multicast group (M) amounts to the sum of total delay experienced by each link of an intermediate router. Formally, the delay encountered by the packets traversing from the root node (s_0) to a destination node(D_f) can be expressed by eqn 7 as:

$$D_{(S_0-D_f)}=\sum_{i=1}^{W} D(L_i)+\sum_{i=1}^{n} D(L_i) \quad [7]$$

The symbol W denotes the collective number of destinations in the system in a particular multicast group of a spanning tree comprising a collection of $n$links.

The first delay term is associated with the number of links with the spanning tree when a packet traverses the path from source to destination. The second term constitutes the delay associated with a packet being transmitted along a specific route. For illustrative purposes, we consider the existence of a route $R_e(s_0,D_f)$ starting from multicast source s_0 to destination D_f with a delay as follows:

$$D_{(s_0\to(D_f\in M)}=\sum_{L_{n,W}\in R_{e(s_{0},D_f)}} D(L_{n,W}) \quad [8]$$

$L_{n,W}$ denotes the total number of packets of links $W\in R_e$ that a packet will have to traverse to get to the destination D_f along a path within the tree T including number of links from source s_0 to multicast group M.

4. Results

Our examination of the AODV and MAODV is divided into two groups: the analytical results obtained from the analytic modelling, and the simulation results produced from the simulation using the NS-2 program.

4.1 Numerical results

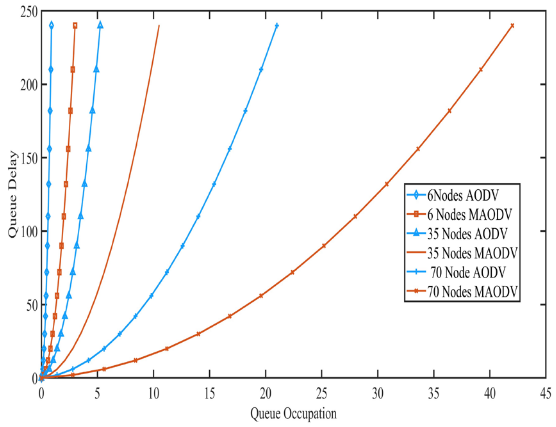

Figure 2: Queuing delay and Queue occupation

For both the AODV and MAODV, Figure 2 shows the relationship between the queuing delay and the queue occupation concerning six nodes for each queue occupation. The MAODV typically has a lower latency than the AODV. There seems to be a similar pattern in the delay when 35 nodes are added to both protocols. Remarkably, the latency seems to be getting shorter as occupation rises.

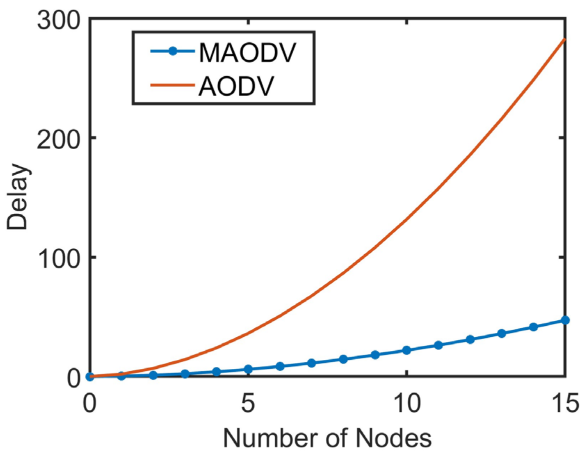

Figure 3: Delay and Number of Nodes

Figure 3 demonstrates how the number of nodes and delay are related. When there are fewer nodes, the delay seems to be smaller, and it gets bigger as there are more nodes. This aligns perfectly with the theoretical forecasts.

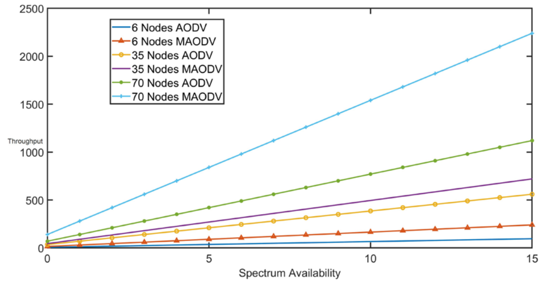

Figure 4: Throughput and spectrum availability

The throughput and spectrum availability from the PUs are related in Figure 4. Throughput and spectrum availability seem to be directly correlated for small networks in general.The AODV and MAODV protocols' theoretical predictions are in line with this. Nevertheless, the throughput drops as both protocols' node counts increase. This has to do with network scalability issues because it is acknowledged that both protocols have a limit beyond which they might not work. Figure 4 illustrates how the MAODV outperforms the AODV in spite of these scaling problems. Figure 5 Illustrates the interdependence between throughput, delay, and number of nodes.

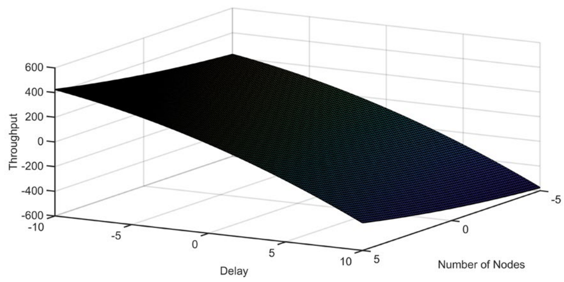

Figure 5: Throughput, Delay and Network Nodes

The model's theoretical predictions for the MAODV protocol are consistent with the surface plot, which displays a high throughput for a reduced latency. This is in agreement with the works in **[31]** wherein the Protocol is energy aware.

4.2 Simulation model

The algorithms were simulated in three scenarios with 6, 35 and 70 nodes and the simulations were run for 100, 300 and 500 simulation seconds respectively. The simulation times were varied to effectively evaluate the performance of the algorithms. Table 1 presents the values of parameters used in the study **[32]**. The following metrics were considered: Routing Path delay, Spectrum Mobility delay and Node Relay delay. The metrics are all delay related which are critical in military intermittent networks. Delay tolerate routing schemes are therefore desirable. Therefore, the selection of metrics was informed by a need to reduce delay in IMCRAHNs. Delays in communication in IMCRAHNs may be critical which may result in the loss of life and the destruction of the equipment.

Table 1. The Simulation parameters

Number of Nodes	6, 35, 70
Simulation Time(s)	100s, 300s, 500s
Size of the Packets (bytes)	512
Simulation Grid (m X m)	500 X 500
Traffic Rate/ Rate	Constant Bit Rate (CBR) 4 packets/s
Nodes Velocity (m/s)	12~15
Range of Transmission (m)	90,120,150,180
Number of connections	15,25,35
Pause Time (s)	0, 50, 100, 250, 350, 500
Number of Radios	2
Routing Algorithms	AODV, MAODV
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)

We evaluated the effectiveness of the multicasting routing protocol. The MAODV was evaluated and compared to AODV. Fig. 6 depicts the RP delay simulation results for MAODV and AODV routing protocols. Fig. 1 shows that for scenarios with 6 and 70 nodes, AODV performed poorly in comparison to MAODV. The performance of the AODV is depicted by the maroon curves. The MAODV incurred less RP delay than AODV because it broadcasts packets to a given zone within which the destination node can be reached or a zone closest to the destination node. Within a zone, paths leading to the destination node are selected while broken links are avoided [33].
MAODV is, therefore, a zonal or geographical-based routing protocol, however, in IMCRAHNs, the possibility of route destruction complicates routing. Furthermore, delays and routing overheads are incurred when the whole network is considered for routing. However, the results in Fig. 6 are clustered as a result, we also analysed the average performance of these schemes in Fig. 7. Furthermore, Fig. 6 is also presented in appendix A with high resolution.

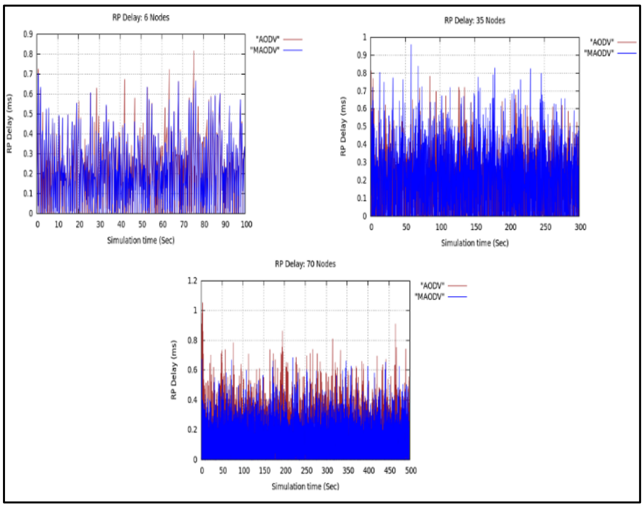

Figure 6. RP simulation Results

Fig. 7 presents the average RP delay results. The average results show that for all the scenarios, the AODV routing protocol experienced more RP delay-related challenges than the MAODV routing protocol. The good performance of the MAODV can be attributed to its effective routing approach discussed under Fig. 1 results and the fact that it is optimized for IMCRAHNs.

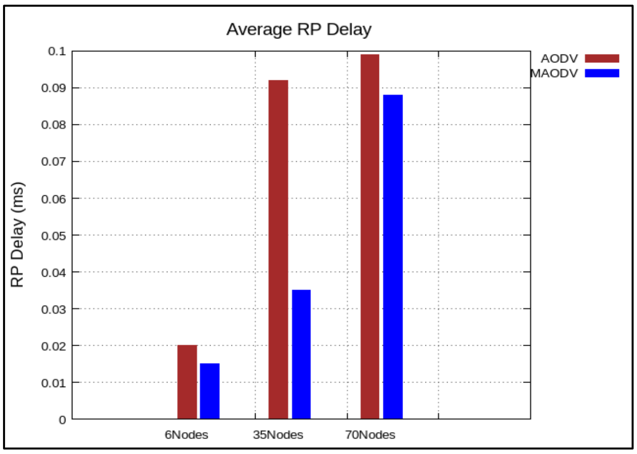

Figure 7. Average RP delay results

4.3 Throughput simulation results for MAODV and AODV

We also evaluated the performance of the schemes based on the achievable throughput in Fig. 8.

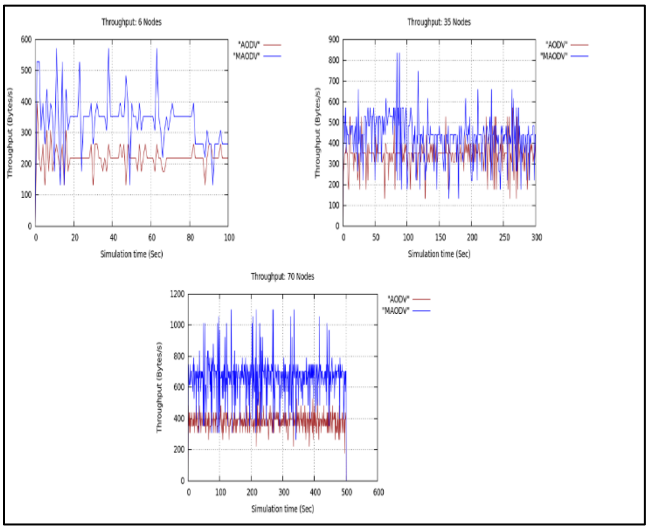

Figure 8. Throughput Simulation Results

Fig. 8 depicts the achievable throughput results of all the network scenarios. The results show that the MAODV achieved more throughput compared to the AODV routing protocol. The multicasting in IMCRAHNs increases the packet delivery success rate when packets are broadcasted in a specific zone within which a destination node can be reached or in the zone closest to the destination node [34] . Zonal routing facilitates faster route discovery and recovery processes. Multicast routing is also subjected to fewer dropped packets because of zonal routing in a small, localized area.

Fig. 8 shows that MAODV had three drops in achievable throughput for the scenario with 6 nodes: for the 0-20 and 40-60 epochs. These are caused by the unavailability of routing paths in the given zone during these epochs. The same gaps were experienced for a scenario with 70 nodes. These gaps were caused mainly by the destruction of nodes and routes.

4.4 The SM delay simulation Results of the MAODV and AODV Routing Protocols

In this Sub-Section, we present the spectrum mobility delay results, and these are depicted in Fig.9.

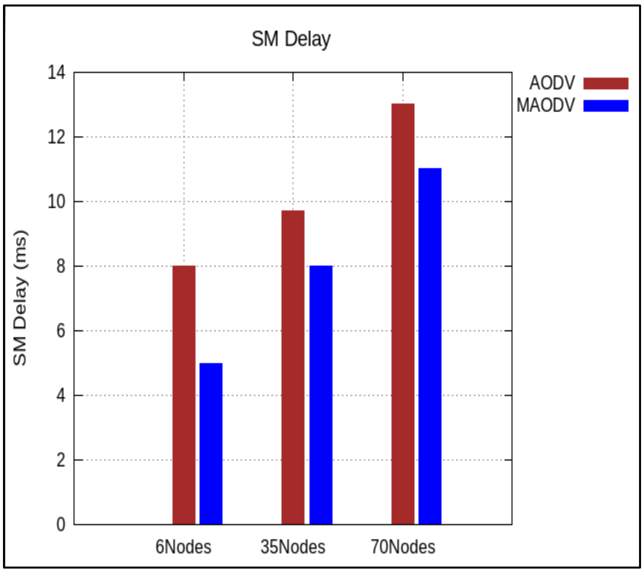

Figure 9. SM delay simulation Results

Fig. 9 shows the SM delay results in which the MAODV was superior to the AODV. Spectrum mobility causes the unavailability of routes, and the frequency of this occurrence degrades the performance of the network. However, both MAODV and AODV are impacted negatively by the SM delay. The MAODV is more efficient because it guarantees route availability before the transmission can take place. As a result, the MAODV has a high likelihood of routes being available. Spectrum mobility is a challenge in IMCRAHNs because a channel detected to be available during sensing can become unavailable just before transmission takes place. If this happens, an affected route cannot be used for data transmission. However, this is minimized in IMCRAHNs through the implementation of zonal routing which increases the availability of routing paths for longer periods. As a result, MAODV incurs less SM delay than the AODV routing protocol.

4.5 The NR Delay Simulation Results of the MAODV and AODV Routing Protocols

In this Section, the schemes were evaluated using the Node Relay delay metric and the results are shown in Fig. 10.

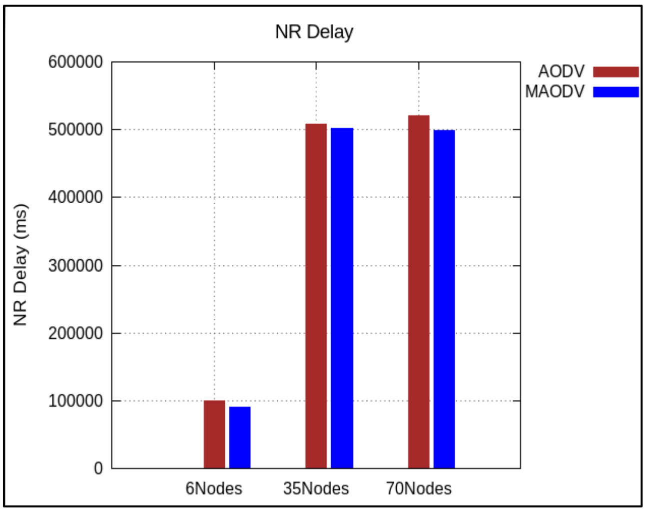

Figure 10. NR Delay Simulation Results

Fig. 10 shows that the MAODV performs better in all aspects. The MAODV routing protocol incurs the least NR delay compared to the AODV routing protocol because, in IMCRAHNs, zonal routing enables routes to be discovered and repaired faster.

The low NR delay in MAODV is because there is a positive correlation between NR delay and SM delay. For a packet to be relayed, the node first accesses the spectrum. As a result, the factors that affect the SM delay also negatively impact the NR delay. A node, therefore, can only relay a packet when the spectrum is available for data transmission [35].

The results presented in Figs. 10 to 14 show that the MAODV routing protocol is superior to the AODV routing protocol in all the simulation scenarios. The MAODV achieved better results in IMCRAHNs routing largely because of the multicasting technique in a localized and focused zone. In a Multicasting-based routing strategy, a network is fragmented logically into smaller zones that contain the destination node, or which are closest to the destination node. The relaying of packets is therefore informed by the proximity of the destination node to or within a given zone.

5. Conclusion

It is reasonable to conclude from a comparison of the AODV and MAODV analytical models that the multicasting technique, or the MAODV protocol, performs better than the unicast AODV protocol. The prediction outcomes of the analytic model are in line with those of [36] in delay tolerant networks which give a high throughput in a highly evolving network.

Furthermore, the simulation results of the study show that the multicasting routing technique implemented in MCRAHNs is more efficient. Zonal or geographical routing facilitates faster discovery of routing paths while enabling faster recovery of broken routing paths. As a result, the MAODV outperformed AODV.

Figs. 7 and 8 also show that for RP delay and throughput simulation results, there were broken routes that were encountered. These are denoted by the drop in achievable throughput in the throughput results. However, despite these challenges of route breakages, the MAODV still performed better. The results show that the MAODV did experience some route breakages which it repaired faster within a given zone.

In the case of SM and NR delay, the results show that the increase in delay is positively correlated with the increase in the number of transmitting nodes. However, in NR and SM delay simulation results, the MAODV routing protocol outperformed the AODV routing protocol. The MAODV routing protocol is more robust and resilient compared to the AODV routing protocol. The implementation of the multicasting routing technique ensures that routes in each zone are available for a longer period which improves MAODV performance. The zonal routing and the use of stable routes reduce SM and NR delays given a higher probability of availability of routing paths for longer durations which in turn, improves the utilization of idle channels.

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Appendix A