Complex Network Analysis of the Relationship Between Reactive Routing and MANET Performance

Diego B. Santi, Júlio C. N. Borges, Mauro Fonseca, Klaus Wehmuth, Anelise Munaretto, Ricardo Lüders

***Abstract*— Reactive routing protocols of MANETs create routing tables whose paths can be represented by a routing network, i.e. the network of links created from routing tables that can change over time. These links are created and destroyed according to the mobile behavior of nodes. Different topologies of the routing network impact the performance of a MANET measured by typical indicators such as PDR (Packet Delivery Rate) and E2E (End-to-End) delay. This work aims at investigating the relationship between the routing network and MANET performance indicators. It is accomplished by representing the routing network as a complex network which is characterized by metrics such as average degree, density and clustering coefficient. The evaluation of a MANET is implemented using OMNeT++, and the Ad hoc On Demand Distance Vector (AODV) routing protocol. The results present the performance indicators and complex network metrics for different speed and number of nodes as well as their correlations. They show a strong negative correlation between PDR and both density and clustering coefficient. However, a strong positive correlation between E2E delay and degree, density and clustering coefficient is observed.**

***Keywords*— Mobile ad hoc network, routing protocol, performance evaluation, complex network.**

I. INTRODUCTION

Mobile Ad hoc Networks (MANETs) have as their main characteristic the absence of infrastructure, with no need for a wireless access point for configuration and management. It consists of nodes that communicate directly or need intermediary nodes to route packets to their destination. These nodes self-organize and seek the best possible management through routing protocols [1]. Routing protocols in ad hoc networks can be classified according to the route management mechanism [2]. The proactive protocols need to maintain information about the routes of all nodes through control packets that are sent at a certain period. Each node has a complete routing table and at every change in the topology and dynamics of the network, the nodes communicate and update their respective tables. Reactive protocols work with routes on demand, there is no need to maintain and look for new routes in case there is no request, reducing the chance of an overload. The reactive Ad hoc on Demand Vector (AODV) protocol works with route request and network auto-configuration without maintaining a complete routing table for all nodes [3].

Network structures arise from several applications such as the World Wide Web, social networks, or the network of spreading diseases, for instance. They are characterized by graphs with particular statistical properties of node connections (complex network models). The analysis of complex networks is applied to the study of the network behavior, its structure, and characteristics such as node degree distribution, and other metrics [4]. In the other hand, metrics such as Packet Delivery Ratio (PDR) and End-To-End delay (E2E) are suitable to analyse the performance of ad hoc networks. However, it does not capture the overall network behavior, which could limit the design of better routing protocols.

It is important to note that we are not proposing an algorithm with improvements for AODV. Our goal is to use this routing protocol as a tool in the simulation to test the hypothesis that typical performance network metrics such as PDR and E2E delay could be correlated with complex network metrics. In this work, PDR and E2E delay metrics were calculated based on the construction of different scenarios using the AODV reactive protocol by varying mobility speeds and number of nodes. These metrics were related to the following complex network metrics: average degree, density and clustering coefficient. We argue if there's a correlation between those metrics that we could use the overall network behavior in terms of complex network metrics to evaluate the performance of an ad hoc network and investigate the factors that contribute or not to a better communication quality. The main objective of this work is to evaluate the performance of an ad hoc network and determine if there are correlations between traditional metrics and complex network metrics.

The paper is organized as follows. Section 2 presents related works. Section 3 describes the simulation configuration, and Section 4 presents and discusses the results. The conclusion and future work are presented in Section 5.

II. RELATED WORK

Several works define network metrics using a routing protocol to assess network behavior in scenarios with varying the number of nodes and the speed of mobility. In [8] PDR and E2E delay metrics were calculated using some protocols such as AODV, to evaluate the impact of using different mobility models. In [9] the mass mobility model was evaluated to investigate the impact of mobility in relation to PDR metrics

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by simulating an AODV network that varies the number of nodes and movement speed. As a result, the authors show that as speed increases, PDR decreases, just as the increase in the number of nodes caused this metric to decrease. In [10] with the variation in the number of nodes and the use of some mobility models and routing protocols, the scenarios were evaluated based on the PDR and E2E delay metrics. It was observed that the increase in the number of nodes was a factor responsible for the degradation of the overall performance of the network, with a decrease in PDR and an increase in E2E delay. Social networks [11], neural networks [12] and transport systems networks [13] are some examples of complex networks where there are connected units that interact dynamically. To understand the behavior of networks, it is possible to carry out the modeling through graphs interconnecting several nodes. These nodes are the representation of connected units, and interactions between them are represented by edges that connect them. In this sense, it is important to define metrics of complex networks such as the average degree, density and clustering coefficient to characterize the behavior of the network over time [14]. Some works have analyzed metrics such as the clustering coefficient and degree to evaluate communication behavior in computer networks. In [16] an improvement was made in the calculation of the node degree to make a communication protocol more effective about the flow of packets. Topological characteristics were also taken into account through the node clustering coefficient, resulting in improvements in the propagation of packets in the network. In order to investigate the impact of clustering on ad hoc networks, the authors of [7] created a metric called clustering performance factor to relate the end-to-end throughput metric. In [15] the objective was to propose a routing algorithm based on clustering coefficient to define node routes with high coefficient, that is, where the nodes are closest. In this way, nodes that have mobility break links more easily, but can re-establish new routes faster to reduce route discovery time. The metric created is the clustered and non-clustered end-to-end throughput. They realized that clustering had an influence on performance. The literature presents comparative studies based on the definition of metrics, alternating number of nodes, mobility model and mobility speed.

III. Methodology

A mobile Ad hoc network is simulated for different scenarios composed by three different number of nodes that move at five different speeds. Each scenario captures the performance of the communication network for slow and fast moving of nodes subject to more or less alternative routes provided by high or low number of nodes, respectively. The performance of the network is measured by traditional metrics such as PDR and E2E delay obtained by simulation. The routing protocol AODV is chosen. It is well known, simple, and consolidated protocol in the literature. Whenever no valid route between origin and destination is found, the AODV protocol generates messages to discover new routes which remain valid for a period of time or when the network topology changes due to the mobility of nodes. This set of routes builds a routing network which is characterized by complex network metrics such as degree, density, and clustering coefficient. The correlation analysis between PDR and degree, density, and clustering coefficient is then performed by Pearson correlation. The same is made for the correlation between E2E delay and those metrics.

A. Evaluation Metrics

The wireless network performance is measured by:

- **Packet Delivery Ratio (PDR):** Rate between the number of packets received by the destination node and the number of packets sent by the source node.
- **End-to-end delay (E2E delay):** Time interval elapsed between sending a packet from the source node and receiving it in the destination node.

The routing topology created by AODV is evaluated by:

- **Degree:** it is the number of edges connected to a node. The average degree is calculated by taking the sum of degrees divided by the number of nodes [5, p. 125].
- **Density:** it is the connectivity ρ of a graph as the fraction between the actual number of edges and the maximum number of edges [5, p. 126].
- **Clustering coefficient:** Consider three vertices u, v and w such that u and w are neighbors of v. The path uvw is said to be closed if and only if u and w are neighbors. They form a loop or triangle in the network. The clustering coefficient is defined as a fraction of two-length paths in the network that are close together [5, p. 200].

B. Simulation Configuration

The proposed simulation is implemented in the network simulator OMNeT++ version 5.7 with AODV as routing protocol. The nodes transmit voice data packets using Constant Bit Rate (CBR) traffic in a constant time propagation model. It means that the propagation time is independent of the traveled distance. The number of nodes is set to 20, 30, 40 and 50. The mobility model is the Mass Mobility in a square area of 650 x 650 meters. The speed of nodes is taken from {0, 1, 2, 3, 4, 5, 6} in m/s. Table I shows the simulation parameters.

TABLE I: Simulation Parameters

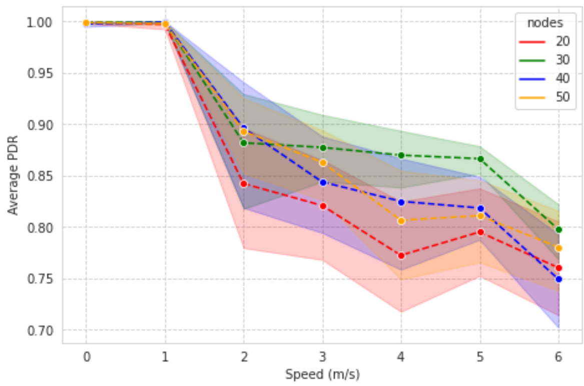
Parameters	Value
Dimensions (m^2)	650 x 650
Routing Protocol	AODV
No. of nodes	{20, 30, 40 and 50}
No. of end-to-end nodes	2
Mobility model	Mass Mobility [17]
Mobility speed (m/s)	{0, 1, 2, 3, 4, 5, 6}
Simulation time (s)	200
Channel type	Acking Wireless [17]
Data type	CBR
Transport protocol	UDP
Physical layer model	Unit Disk Radio [17]
Radio communication range (m)	250
Radio interference range (m)	0
Active route timeout (s)	3

The nodes performing the of end-to-end communication are located in the upper left and lower right corners of the square area. They cannot communicate directly to each other due to the radio range limits. Therefore, intermediate nodes are necessary for communication, which may or may not be moving. Each scenario is averaged over 30 simulation runs for computing average values of PDR, E2E delay, degree, density, and clustering coefficient with confidence interval of 95%.

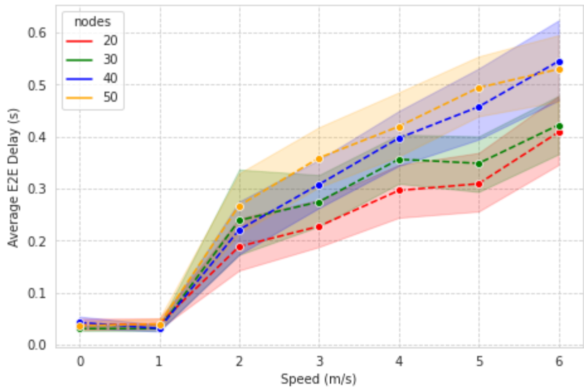
IV. Results and Discussion

The performance of the end-to-end communication is shown for PDR and E2E delay. The results for degree, density, and clustering coefficient characterize the routing network. The relationship between routing and performance is then shown by correlations between those metrics.

A. PDR and E2E delay



(a) Average PDR.



(b) Average E2E delay.

Fig. 1: Average PDR and E2E delay with 95% confidence interval (shadow areas) versus speed of nodes in a network with 20, 30, 40 and 50 nodes.

Figure 1a shows the average PDR with 95% confidence interval (shadow areas) in a network of 20, 30, 40 and 50 nodes moving at different speeds. At low speed (zero and 1 m/s), the AODV protocol performs route discovery and finds paths that remain valid most of the time. Therefore, packets are sent without creating new routes, which explains high PDR values at low speeds. By increasing the speed of nodes (2 m/s and higher), the route discovery procedure should create routes more frequently due to broken links. In this case, the average PDR decreases due to the overhead of discovering routes, causing loss of packets [18]. However, a slight increase of PDR for 20 nodes is observed from 4 to 5 m/s which is probably due to the uncertainty included in the confidence interval.

Note that PDR is better for 40 and 50 nodes moving slowly, but it tends to be worst when the speed increases. It occurs because AODV tries to repair broken links by sending broadcast messages requesting new routes. The communication overhead is then increased with more nodes, which generate more control packets and bigger routing tables. Therefore, more nodes are not necessarily better for AODV.

Figure 1b shows the average E2E delay for 20, 30, 40 and 50 nodes with confidence interval of 95% (shadow areas) versus the speed of nodes. The E2E delay for 50 nodes are higher than others. Moreover, it increases as the speed of all nodes increases. As the speed of nodes increases, the communication links between them break more frequently and the time needed to compute new routes affects the delivery time of packets.

Furthermore, a packet can be forwarded to a close neighbor node which is moving in the opposite direction of the destination node. In all the scenarios, the E2E delay increases for speeds of 2 m/s and above due to the greater number of broken links, and to the need of requesting and establishing new routes. According to [6], the E2E delay increases as the node speed increases. The authors show that the AODV protocol can be overloaded with many broken links. Therefore, it cannot quickly solve this problem to minimize the packet loss and E2E delay.

B. Degree, density, and clustering coefficient

Figure 2 shows the average degree with confidence interval of 95% (shadow areas) of the routing network for 20, 30, 40 and 50 nodes versus the speed of nodes. When intermediate nodes are stopped or moving at low speeds (1 m/s), the average degree tends to stabilize between 1.5 and 2. It means that two links are established in average for each node. It also suggests that AODV is able to find a route actives for a long period of time with low number of hops. In this case, an increase in the number of nodes has minor influence on the average degree. For a node speed higher than 1 m/s, the average degree increases because AODV floods the network with control messages. They are necessary to respond route requests which increase the number of links in the routing network. The average degree is also positively influenced by the number of nodes because AODV creates more connections during the route discovery phase. The mobility of nodes forces AODV to constantly search for valid routes which often modify the routing network, resulting in high values of average degree.

Figure 3a shows the average density of the routing network with confidence interval of 95% (shadow areas) for 20, 30, 40 and 50 nodes versus the speed of nodes. The density is approximately constant for the static case or at low speed (1m/s), because the number of routes is independent of the number of nodes. It increases as the number and speed of nodes increase. In this case, what determines density is

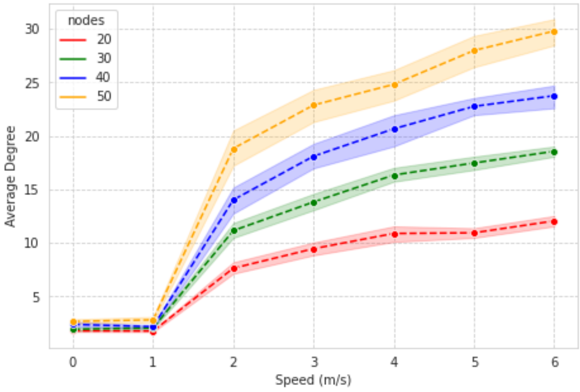


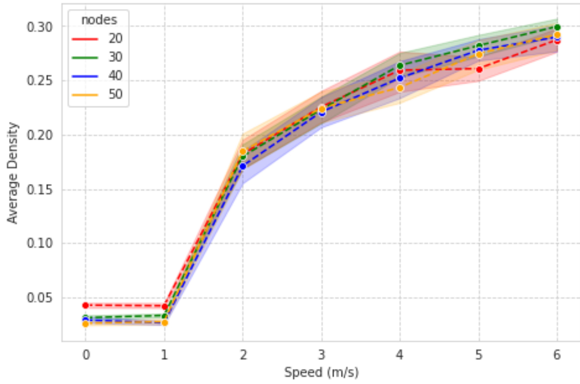
Fig. 2: Average degree with 95% confidence interval (shadow areas) versus speed of nodes in a network with 20, 30, 40 and 50 nodes.

mainly the number of nodes because the number of possible connections is increased as the number of nodes increases. However, it is bounded by the radio range which only allows connections between nearby nodes. Similarly to the average degree, the mobility of nodes forces AODV to constantly search for valid routes, which yields to high densities. By increasing the speed of nodes, the average density of the routing network is increased due to AODV activity.

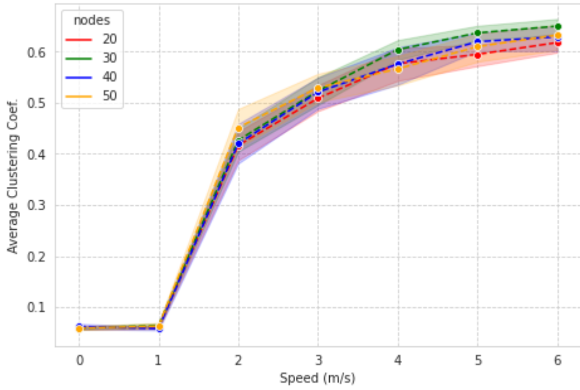
Figure 3b shows the average clustering coefficient of the routing network with confidence interval of 95% (shadow areas) for 20, 30, 40, and 50 nodes versus the speed of nodes. When intermediate nodes are stationary or moving at 1 m/s, the clustering coefficient tends to be zero because AODV creates a small number of triangles (or less alternative routes) in the routing network. Therefore, what determines the average value of the clustering coefficient is the route discovery period in which the network suffers a flood of route request packets. It increases the number of triangles and the clustering coefficient as well. Therefore, the increasing number of nodes increases the average clustering coefficient. When the speed of nodes is higher than 1 m/s, AODV is forced to constantly search for new routes, and the average clustering coefficient is increased.

C. Correlation Analysis

This section presents the correlation analysis of PDR and E2E delay with the average degree, density and clustering coefficient. We argue that typical performance metrics of PDR and E2E delay can be correlated to the complex network metrics of the routing network created by AODV. The six scatter plots generated by {PDR, E2E delay} $\times$ {degree, density, clustering} are shown in Fig. 4. It shows a negative correlation between PDR and the complex network metrics, and a positive correlation between E2E delay and those metrics. In other words, more dense routing networks yield to poor network performances (low PDR and high E2E delay).



(a) Average density.



(b) Average clustering coefficient.

Fig. 3: Average density and clustering coefficient with 95% confidence interval (shadow areas) versus speed of nodes in a network with 20, 30, 40 and 50 nodes.

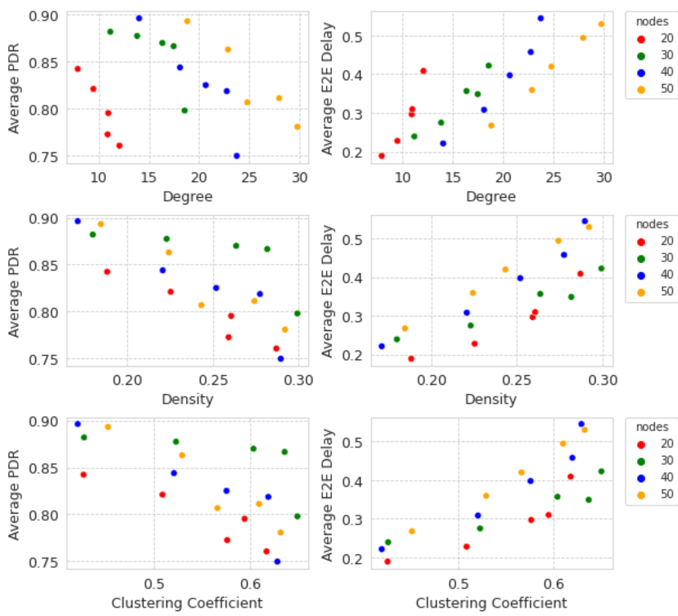


Fig. 4: Scatter plots for {PDR, E2E delay} $\times$ {degree, density, clustering}.

This behavior is quantified by the corresponding Pearson correlations as shown in Table II, considering the speed of nodes higher than 1 m/s.

TABLE II: Correlation between metrics and R^2 coefficient

Complex network metric	**PDR**		**E2E delay**	
	Corr.	R^2	**Corr.**	R^2
Average degree	-0.21	0.0441	0.83***	**0.6889**
Network density	-0.74***	**0.5476**	0.82***	0.6724
Clustering coefficient	-0.67**	0.4489	0.82***	0.6724

Significance: * (p-value<.05), ** (p-value<.01), *** (p-value<.001)

According to Table II, there is a strong negative correlation between PDR and both density and clustering coefficient. Therefore, dense networks yields to low PDR values because they generate more control packets and big routing tables with high communication overhead. The result for the clustering coefficient is similar to the density because they are strongly correlated to each other. However, a weak correlation is observed between PDR and degree. The coefficient of determination R^2 of Table II means that a simple linear regression model of the average PDR as a function of the network density explains 54.76% of the data. According to Fig. 4, the degree is limited by the number of nodes. In this case, the scatter plot of Degree $\times$ Average PDR is strongly influenced by the number of nodes, which can explain the weak correlation between PDR and degree.

Table II also shows a strong positive correlation between E2E delay and degree, density, and clustering coefficient. The E2E delay increases as these metrics increase. Therefore, the degree, density, and clustering coefficient are capturing an even more relevant effect of the communication overhead of AODV caused by broken links in the E2E delay. The coefficient R^2 means that a regression model of the average E2E delay as a function of the average degree explains 68.89% of the data.

In summary, the results show that complex network metrics have correctly captured the AODV behavior. A strong negative correlation was observed between PDR and both network density and clustering coefficient. A strong positive correlation was observed between E2E delay and degree, density and clustering coefficient. A simple regression model captures well the average PDR as a function of the network density, and the average E2E delay as a function of the average degree.

V. CONCLUSION

In this work, we have analyzed the effect of increasing the speed and number of nodes in the performance of a mobile ad hoc network using the AODV routing protocol. A routing network created by AODV is characterized by complex network metrics such as average degree, density and clustering coefficient. These metrics are further correlated with traditional network performance indicators such as PDR and E2E delay. The results suggest that AODV has poor performance (low PDR and high E2E delay) when more links are created. High speeds generate more broken links which force the protocol to constantly broadcast route requests with high communication overhead. These aspects of AODV have been correctly captured by the results of complex network metrics, which showed a poor network performance for more dense routing networks. Traditional performance metrics such as PDR and E2E delay are good for evaluating existing or simulated networks. However, they provide less information for designing new routing algorithms. In the future, complex network metrics can be used to obtain structural characteristics of the routing network and improve routing protocols. Other routing protocols should also be explored.

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