SRN Models for Analysis of Multihop Wireless Ad Hoc Networks

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ABSTRACT. Mobile Ad hoc Networks (MANETs) are becoming very attractive and useful in many kinds of communication and networking applications. Due to the advantage of quick construction and numerical analysis of analytical modelling techniques, such as Stochastic Petri nets, Queueing Networks and Process Algebra, have been broadly used for performance analysis of computer networks. In addition, analytical modelling techniques generally provide the best insight into the effects of various parameters and their interactions. To the best of our knowledge, there is no analytical study that investigates the effect of various factors of multihop ad hoc networks, such as communication range, density of nodes, random access behavior, mobility patterns, speed of nodes, traffic patterns, and traffic load, on the performance indices such as packet delay and network capacity. The main objective of this work is designing an analytical framework that can be used to study the effect of all these factors on the performance of MANETs, where nodes move according to random waypoint mobility model. We employ a verbose modelling approach which includes organizing a framework into several models to break up the complexity of modelling the complete network, and make it easier to analysis each model of the framework as required. The proposed framework can be used to evaluate any of transport, network, or data link layer protocols. The proposed models are validated using extensive simulations.

1 Introduction

Traditional wireless communication networks, namely cellular and satellite networks, require a fixed infrastructure over which communication takes place. Accordingly, considerable effort and resources are required for such networks to be set up, before they can actually be used. In cases where setting up an infrastructure is a difficult or even impossible task, such as in emergency/rescue operations, military applications or disaster relief, other alternatives need to be devised. Mobile Ad hoc Networks (MANETs) are stand alone wireless networks that lack the service of a backbone infrastructure [1]. They consist of a collection of mobile nodes, where the nodes act as both sources and routers for other mobile nodes in the network. A node can send a message to another one beyond its transmission range by using other nodes as relay points and thus a node can function as a router. This mode of communication is known as wireless multihop.

Mobile Ad hoc Networks share many of the properties of wired and infrastructure wireless networks but also has certain unique features which come from the characteristics of the wireless channel. Nodes in MANETs are free to move randomly; thus, the network topology changes rapidly at unpredictable times. Therefore, the nodes need to collect connectivity information from other nodes periodically. Mobility is a crucial factor affecting the design of MANET's protocols, including Medium Access Control (MAC), Transmission Control Protocol (TCP), and routing protocols.

High performance is a very important goal in designing communication systems. Therefore, performance evaluation is needed to compare various architectures for their performance, study the effect of varying certain parameters of the system and study the interaction between various parameters that characterize the system. It is to be noted that most of research that studies the performance of MANET were evaluated using Discrete Event Simulation (DES) utilizing a broad range of simulators, such as NS2 [2], OPNET [3], and GloMoSim [4]. The principal drawback of DES is the time taken to run such models for large, realistic systems, particularly when results with high accuracy (i.e., narrow confidence intervals) are desired. In order to get a reliable value, one has to run simulation tens of iterations with different seed values of a random generator. In other words, it tends to be expensive. A large amount of computation time may be needed in order to obtain statistically significant result. In highly variable scenarios, with number of nodes ranging from tens to thousands, node mobility varying from zero to tens of m/s, the simulation time of most current systems will increase dramatically to an unacceptable level.

Due to the advantage of quick construction and numerical analysis of analytical modelling techniques, such as Petri nets and process algebra, have been used for performance analysis of networks. In addition, analytical modelling is a less costly and more efficient method. It generally provides the best insight into the effects of various parameters and their interactions [5]. Hence analytical modelling is the method of choice for a fast and cost effective evaluation of a network protocol.

Ad hoc networks are too complex to allow analytical study for explicit performance expressions. Consequently, the number of analytical studies of MANET is small [6-10]. In addition, most of these studies have many drawbacks, which can be summarized as follows:

1. Most of analytical research in MANET suppose that the nodes are stationary or the network is connected all the times to simplify the analytical analysis.
2. Most of analytical research in MANET study the behaviour of one protocol in a specific layer, not the whole network. For example in [11-16] they only proposed models for MAC protocols in Data Link Layer.
3. To reduce the state space of the analytical models of MANET, most of researches are macroscopic (dynamics of actions are aggregated, motivated by limit theorems) and not scalable.
4. Some of research is restricted to analysis of single hop ad hoc networks.
5. To simplify the analysis, most of research study MANETs in the case of saturated traffic load (i.e. all the time every node has a packet to send).

To the best of our knowledge, there is no analytical study that investigates the effect of various factors of ad hoc networks, such as communication range, density of nodes, random access behavior, mobility patterns, speed of nodes, traffic patterns, and traffic load, on the performance indices such as packet delay and network capacity. This work introduces an analytical framework that can be used to study the effect of all these factors on the performance of MANETs. The proposed framework is organized into several models to break up the complexity of modelling the complete network, and make it easier to later analysis of each model of the framework as required. The proposed framework can be used to evaluate any of transport, network, or data link layer protocols. In addition this framework can be used to study the effect of the interaction between different protocols in different layers on the performance of MANETs.

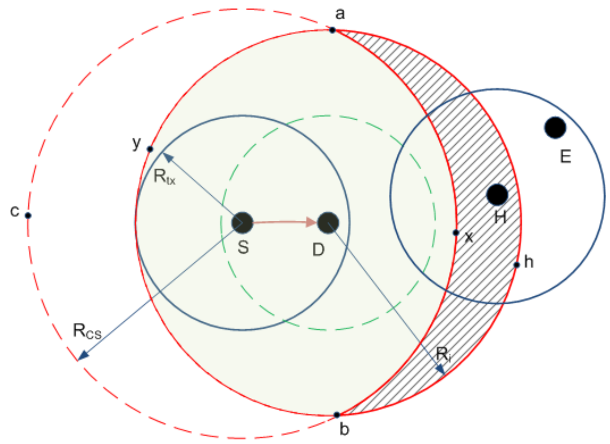

Fig. 1. One hop communication

2 Network Model And Assumptions

To develop a Stochastic Reward Net (SRN) models for MANET, we consider a network consisting of N nodes that are distributed in a square area of dimension $L\times L$ according to a mobility model, such as random waypoint. All nodes are independent and behave identically. Each node is equipped with omni-directional antenna and has a fixed transmission range R_{tx}. Each node in the network is a source of traffic, where it generates packets with rate λ. The destination of any source is chosen from other nodes randomly. For the end-to-end connection, if the destination is not in the transmission range of the source, the packets are routed through N_h hops through neighbour nodes. The neighbour nodes (intermediate nodes) are used as connection relays to forward packets to destinations. Therefore, the mobile nodes work as both sources and routers for other mobile nodes in the network. We suppose that each node forward the same average number of packet per unit time (λ_r) to other neighbour nodes. The traffic load in the network is represented by λ and λ_r. The number of routed packets per unit time (λ_r) is one of the network layer model parameters. An expression for λ_r is derived in Section 4.

In wireless networks, all nodes with multi-directional antennas have three radio ranges related to the wireless radio: transmission range (R_{tx}), carrier-sensing range (R_{cs}) and interference range (R_i). To illustrate these ranges, Figure 1 shows one hop communication between the source node *S* and destination node *D*, where the circles with radii R_{tx}, R_{cs} and R_i present the transmission range of the node *S*, carrier sensing range of the node *S* and interference range of the node *D*, respectively.

Carrier sense range is a physical parameter for a wireless radio. It depends on the sensitivity of the antenna. Any transmissions from other nodes in the carrier sense range of a node *S* will trigger carrier sense detection, and *S* detects the channel as busy. If the channel is detected to be busy, node *S* will wait for the channel to become idle for at least the duration of distributed inter-frame space (DIFS) before it starts trying to transmit a packet. The area covered by the carrier sense range of a node is called carrier sense area for the node. The nodes located in the carrier sensing area are called carrier sensing nodes (N_{cs}).

All nodes located within the area covered by the transmission range of a node *S*, called neighbour nodes, can receive a packet from *S* or send a packet to *S* successfully, if there is no interference from other radios. The area covered by the transmission range of a node is called capture area for the node. If a node *S* transmits to a node *D*, as shown in Figure 1, any transmission from any node located within the interference range of *D* interferes with the signal sent by *S*.

Transmission and carrier sense range are determined by the transmission and reception power threshold and path loss of signal power. To simplify analysis, we assume that both carrier sense and transmission ranges are fixed and identical in all the nodes. The interference range of any node varies depending on the distance between *S* and the destination and the sending and receiving signal power.

The hidden area (the dashed area shown in Figure 1) is the area covered by the interference range of the destination node *D* and not covered by the carrier-sensing range of the source node *S*. The nodes located in the hidden area are called the hidden nodes. For example, as shown in Figure 1, the node *H* is in the interference range of *D* and out of the carrier sensing range of *S*. Therefore, the node *H* is hidden from *S*. The node *S* will not be able to hear transmission by the hidden node *H*. Consequently, if it transmits packets to the node *D* at the same time, there will be packet collisions at *D*. The hidden nodes problem is a well-known problem in multihop ad hoc networks.

The nodes located in the intersection of the carrier sensing range of the source and the interference range of the destination are called interfering nodes. For example, for the source and destination nodes *S* and *D* shown in Figure 1, the interfering nodes are located in the shaded area. Any transmission from these nodes is sensed by *S* and interferes with the transmission from *S*. For random waypoint mobility model, we introduced a mathematical analysis in [17] and [18] to compute the average number of carrier sensing nodes (N_{cs}), interfering nodes (N_i) and hidden nodes (N_H).

3 Proposed Framework

MANETs are a multi-layer problem. The physical layer must adapt to rapid changes in link characteristics. The multiple access control layer should allow fair access, minimize collisions, and transport data reliably over the shared wireless links in the presence of hidden or exposed terminals and rapid changes. The network layer protocols should determine and distribute information used to calculate paths in an efficient way. The transport layer should be able to handle frequent packets loss and delay that are very different than wired networks. In addition, the topology of MANET is highly dynamic because of frequent nodes mobility. Thus, there are many interacting parameters, mechanisms, and phenomena in the area of mobile ad hoc networking. Therefore, Ad hoc networks are too complex to allow analytical study for explicit performance expressions.

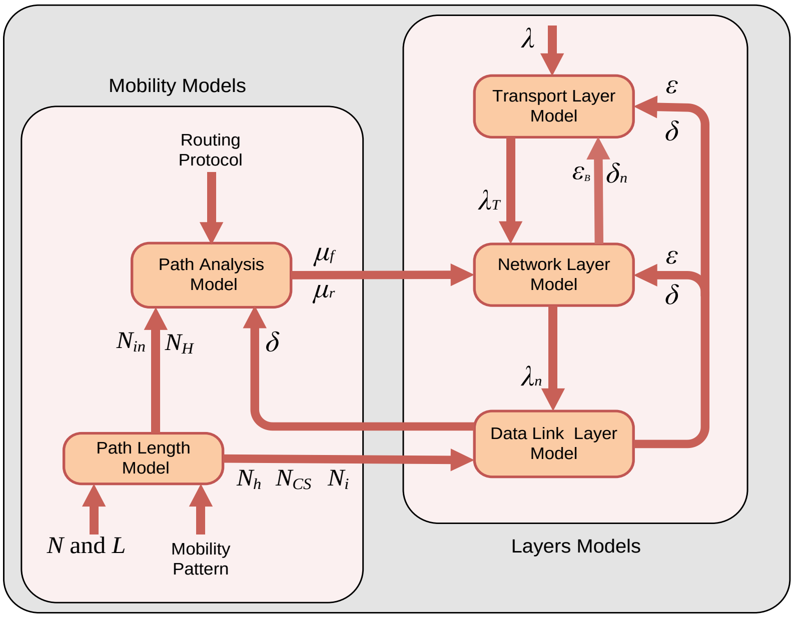

Fig. 2. Proposed framework for modelling MANET

To overcome all drawbacks of other research explained in Section 1, we propose an analytical framework that can be used to evaluate MANETs or a specific protocol in any layer. To present an approach for the modelling and analysis of large-scale ad hoc network systems, there are two requirements in advance. First, the model should be detailed enough to describe some important network characteristics that have a significant impact on performance. Second, it should be simple enough to be scalable and analyzable. It is clear that these two requirements are contradictory. Therefore, to solve this problem, we will model the MANET by a framework that consists of four models, as shown in Figure 2, instead of building one analytical model for the whole network. These four models and the interactions between them will be similar to the four main layers and their interactions in TCP/IP model.

Figure 2 illustrates the analytical framework for modelling mobile ad hoc networks. It consists of five models which are divided into two groups; Mobility Models and Layers Models, as shown in Figure 2. The five models interact with each other by exporting and importing some parameters from other models, as shown in Figure 2. The mobility models are used to make analysis of the path between any source and destination. It consists of two models, Path Length Model and Path Analysis Model. According to the number of nodes (N), mobility pattern (random way point, random walk point, free way, etc.), and the size of the network area (L^2), the Path Length Model is used to compute the expected number of hops between any source-destination pair (N_h). According to the routing protocol (AODV, DSR, SSA, LMR, etc.) and N_h , the Path Analysis Model is used to study connection availability of the path and calculates the average rate of failure (μ_f) and repair (μ_r) of any path between any source and destination. The Path Length Model is a mathematical model, whereas the Path Analysis Model is Stochastic Reward Net model, which have been introduced in [17] and [18], respectively.

The Layers models consist of three models; Data Link Layer Model, Network Layer Model, and Transport Layer Model. Data link layer protocols (MAC protocols) are modelled by the Data Link Layer Model. This model uses the throughput of the Network Layer Model (λ_n) to compute the packet loss probability (ε) and the average delay of packets (δ) in data link layer. In [19], we introduced the Data Link Model. The actions in the network layer are modelled by the Network Layer Model. It uses μ_r, μ_f, λ_T (the throughput of Transport Layer Model) and ε to calculate the average number of packets per unit time that is sent to Data Link Layer model (λ_n), Packet loss probability when the node buffer is full (ε_B), and the average delay of packets in the Network Layer Model (δ_n). The network layer SRN model is introduced in Section 5. The Transport Layer Model (TLM) represents the analytical model for any of the transport layer protocols such as TCP or UDP. The inputs of the TLM are λ, ε_B, δ_n, and ε, and the output is λ_T. To simplify the analytical analysis, only UDP protocol is adopted as a transport layer protocol. Because of its simplicity, modelling of UDP protocol is included in network layer model introduced in Section 5.

The proposed models are solved iteratively using fixed point iteration technique to compute the required performance indices, such as the average delay and throughput per hop. This is explained in Section 4. Also, Section 4 shows how to use the performance indices per hop to compute the performance indices per path.

4 Traffic Load And Packet Forward Rate

The traffic load in the multihop ad hoc networks depends on the packets generation rate (λ) and packets forward rate (λ_r) per node. Packets generation rate is a network parameter, whereas the packets forward rate depends on λ and other network parameters such as network size, number of nodes, and mobility model. This section derives an expression for λ_r.

Figure 3 shows N_h hops communication path between the source node S and destination node D, where λ_t is the average number of packets that is successfully sent by any node per unit time, and λ_1, λ_2, …., λ_{Nh} are the average number of packets sent by the source S and received by the nodes R_1, R_2, …. , D, respectively. Throughput ratio (α) is the ratio between the average number of received and successfully transmitted packets per node per unit time. Because all nodes are similar and behave identically, we suppose that throughput ratio for all nodes are equal. The throughput ratio can be computes as follows:

$$\alpha = \frac{(\lambda_t - \lambda_1) + \lambda_1}{\lambda_r + \lambda} = \frac{\lambda_t}{\lambda_r + \lambda} = \frac{\lambda_1}{\lambda} = \frac{\lambda_t - \lambda_1}{\lambda_r}$$

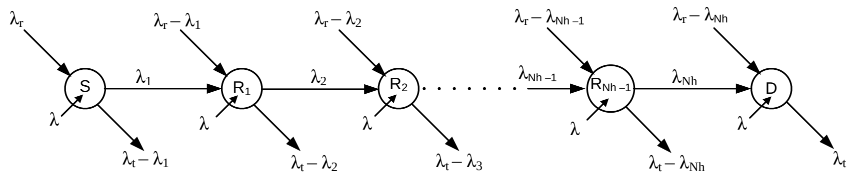

Fig. 3. A network communication path

Therefore, the average number of packet that the node R_1 received from the source S per unit time is $\lambda_1 = \alpha\,\lambda$. For the node R_1, the throughput ration is computed as follows:

$$\alpha = \frac{(\lambda_t - \lambda_2) + \lambda_2}{(\lambda_r - \lambda_1) + \lambda_1 + \lambda} = \frac{\lambda_t}{\lambda_r + \lambda} = \frac{\lambda_t - \lambda_2}{(\lambda_r - \lambda_1) + \lambda} = \frac{\lambda_2}{\lambda_1}$$

So, the average number of packet that are sent by S and received by R_2 is

$$\lambda_2 = \alpha\,\lambda_1 = \alpha^2\,\lambda$$

In the same way, we can deduce that the average number of packet that a node R_k received from the source S per unit time is

$$\lambda_k = \alpha^k\,\lambda \tag{1}$$

Consequently, the average number of packets received by the destination D per unit time, which represents the throughput per path, is

$$Throughput = \lambda_{N_h} = \alpha^{N_h}\,\lambda \tag{2}$$

The number of packets sent by a source S and forwarded (routed) by the intermediate nodes (routers) between the source S and destination D in the path can be computed as follows:

$$\lambda_x = \lambda_1 + \lambda_2 + \ \ldots\ldots + \lambda_{N_h - 1}$$

From equation 1 and 2, λ_x can be computed as

$$\lambda_x = (\alpha + \alpha^2 + \cdots + \alpha^{N_h - 1}) \cdot \lambda \tag{3}$$

If the number of sources in the network is N_s, the average number of routed packets per unit time (λ_r) is

$$\lambda_r = N_s \cdot \lambda_x = N \cdot \lambda_r \tag{4}$$

From equation 3 and 4, the average number of routed packets per node is

$$\lambda_r = (\alpha + \alpha^2 + \cdots + \alpha^{N_h - 1}) \cdot \frac{N_s}{N} \cdot \lambda \tag{5}$$

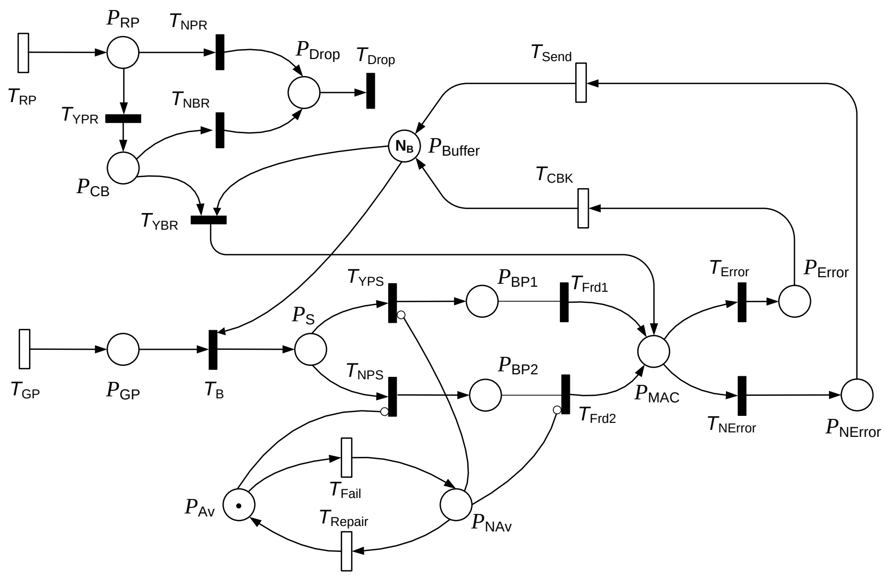

Fig. 4. Network layer model

5 Network Layer Model

The main goal of network layer protocols (Routing Protocols) is the correct and efficient route establishment and maintenance between a pair of nodes in order that the messages are sent or forwarded reliably and in a timely manner. In addition, because the nodes work as a router, the routing protocols maintain information about the routes in the network to be used to forward any received packets. The design of MANET routing protocols is a challenge because they operate in resource-constrained devices and networks with highly dynamic topologies.

The proposed network layer model is shown in Figure 9. It is a Stochastic Reward Net (SRN) model for network layer events in MANETs. Transition T_{GP} represents the generation of packets in the transport layer. When transition T_{GP} fires, a token is deposited in the place P_{GP}. The mean firing time of T_{GP} is the mean time of generation of UDP packets in transport layer. The place P_{Buffer} contains tokens corresponding to the free buffer spaces in the current node. The initial number of tokens in P_{Buffer} (N_B) is the total number of free buffer spaces in the node. The firing of immediate transition T_B reserves a buffer space for outgoing packets by removing a token from P_{Buffer} and depositing a token into the place P_s which represents receiving of packets by the network layer.

When a token arrives in the place P_s, there are two possibilities at this point. The first, the path to the destination is available, so the transition T_{YPS} fires moving the token from the place P_s to the place P_{BP1}. The firing of transition T_{Frd1} moves the token from P_{BP1} to P_{MAC} which represents forwarding the packet from the network layer to the MAC layer. The second, the path to the destination is not available, therefore the transition T_{NPS} fires depositing the token to the place P_{BP2}. If the route is recovered or established, the transition T_{Frd2} fires to forward the packet to the MAC layer.

The places and transitions P_{MAC}, P_{Error}, P_{NError}, T_{Error}, $\mathrm{T}_{\mathrm{NErrror}}$, T_{CBK}, and T_{send} present the interaction with the Data Link Layer Model presented in [19]. The token in the place P_{MAC} represents that the MAC layer received the packet and started to send it. If the MAC layer failed to transmit the packet due to packet collision or interference, the MAC protocol drops the packet and sends a CBK (Call Back) error message to the network layer. This represented by the place P_{Error} and firing of transitions T_{Error} and T_{CBK}. The firing of timed transition T_{CBK} presents the completion of the error detection and dropping the packet, after which one place buffer in the current node is released by returning a token to the place P_{Buffer}. On the other hand, successful transmitting and receiving the packet are presented by fringe of transition T_{NError}, which moves the token from P_{MAC} to P_{NError}, and firing of transition T_{Send} that returns the token back to the place P_{Buffer} representing increasing the free buffer space by one.

The firing probability of T_{Error} (ε) is the probability of CBK error (packet dropping probability), whereas the firing probability of T_{NError} is ($1-\varepsilon$). The one node detailed model in Data Link Layer Model [19] is used to compute ε. The firing rate of the timed transition T_{Send} ($Rate(T_{Send})$) and T_{CBK} ($Rate(T_{CBK})$) are the average number of packet sent and dropped by the MAC protocol per unit time which are computed from the Data Link Layer Model [19].

In MANETs, each node has a routing table that indicates for each destination which is the next hop and number of hops to the destination. The main function of the routing protocols is building and updating the routing table. The routing protocols work in the network layer. For any packet entering the network layer, the routing protocol checks all available paths to the destination and chooses the best one. Because of mobility of nodes, there are frequent failures for paths between sources and destinations. The average time of failure of any path between any source and destination depends on the density distribution of nodes and the type of mobility pattern. For any path failure, the routing protocol tries to recover the path to the destination. The average time of the path recovery depends on the type of routing protocols, density of nodes, and mobility pattern.

The places P_{Av} and P_{NAv}, and transitions T_{Fail} and T_{Repair} model the effect of path failure and repairing process. The token in P_{Av} means that the path between the source and destination is available. Whereas, the token in P_{NAv} means that the path between the source and destination is not available. The timed transitions T_{Fail} and T_{Repair} present the completion of failure and repair of the path between the source and destination, respectively. The rate of firing of transitions T_{Fail} (μ_f) and T_{Repair} (μ_r) are the average rate of failure and repair of any path, respectively, which are computed using the Path Analysis Model that we proposed in [18]. The inhibiter arcs from places P_{AV} and P_{NAv} to transitions T_{Frd2}, T_{NPS} and T_{YPS} ensure that if there is no path to the destination in the routing table, the packet (token) will not forward from the routing layer (P_{s}) to the data link layer (P_{MAC}).

Any node in MANET may work as a source, destination or router. The neighbours of any node may send packets to it to forward them to another node (works as a router) or absorb them (works as destination). The firing of timed transition T_{RP} and depositing a token in the place P_{RP} present the completion of receiving a packet from a neighbour node. The firing rate of T_{RP} depends on the average number of received packet to forward per unit time (λ_r). Section 4 derived an expression for λ_r. If the path that is required by the received packet is not available, the node drops the packet immediately. This is modelled by the place P_{Drop} and transitions T_{NPR} and T_{Drop}. Otherwise, the node tries to save the packet in the buffer which is presented by transition T_{YPR} and place P_{CB}.

Firing of transition T_{NBR} means that the buffer is full ($\#P_{Buffer} = 0$) and the node is unable to forward the packet which is dropped. If the buffer can accommodate a packet ($\#P_{Buffer} > 0$), the packet enters a queue and waits in order to be processed by MAC protocol. This is presented by firing transition T_{YBR} that moves a token from P_{CB} to P_{MAC}. Transitions T_{GP} and T_{RP} are assigned with guard functions that preventing firing of these transitions when the buffer is full ($\#P_{Buffer} = 0$). If ψ is the average probability that any path in the network is available, the firing probabilities of the transition T_{YPR} and T_{YPS} are ψ, whereas the firing probabilities of transitions T_{NPR} and T_{NPS} are $(1- \psi)$. The probability of the path availability is computed using the Path Analysis Model that we proposed in [18].

As explained in Section 3, the proposed frame work consists of three main SRN models; Data Link (MAC) Layer Model, Path Analysis Model, Network Layer Model. To compute the required performance indices, such as delay and throughput, the three models are solved iteratively using the fixed point iteration technique. The following procedure and Figure 2 summarize the iterative process to solve the proposed models to compute the delay per hop and throughput ratio which is used to compute the end-to-end delay and throughput per path:

Step 1: Using the Path Length Model, the parameters N_H, N_{cs}, N_h, and N_i, are computed.

Step 2: Solve the Data Link Layer Model using the procedure introduced in [19] to compute ε and δ considering that $\lambda_n = \lambda$.

Step 3: Solve the Path Analysis Model to compute μ_f and μ_r.

Step 4: Considering that $\alpha = 0.5$, as an initial value, the Network Layer Model is solved to compute the new value for α and λ_n. Also, any of the performance metric τ^n, such as throughput per hop, is computed, where n is the number of iteration.

Step 5: If $n = 1$ (initial iteration), increase n by one and go to Step 2.

Step 6: Compute the error of the performance metric using the following equation

$$\mathrm{err}(\tau)=|\tau^n - \tau^{n-1}| / \tau^n$$

Step 7: If the err(τ) is less than a specified threshold, stop the iteration process, otherwise increase n by one and go to Step 2.

The number of iterations depends on the error threshold. In all validation scenarios introduced in the validation section, the error threshold is set to 0.05. In all cases the convergence of the performance metric is achieved in only a few iterations.

6 Validation and Results

In this section, the proposed model is validated by making extensive comparisons of its results with the results of many simulation experiments. The simulation results are obtained by using ns-2 simulator [2], whereas the analytical results derived from the proposed models are obtained using SPNP tool [20].

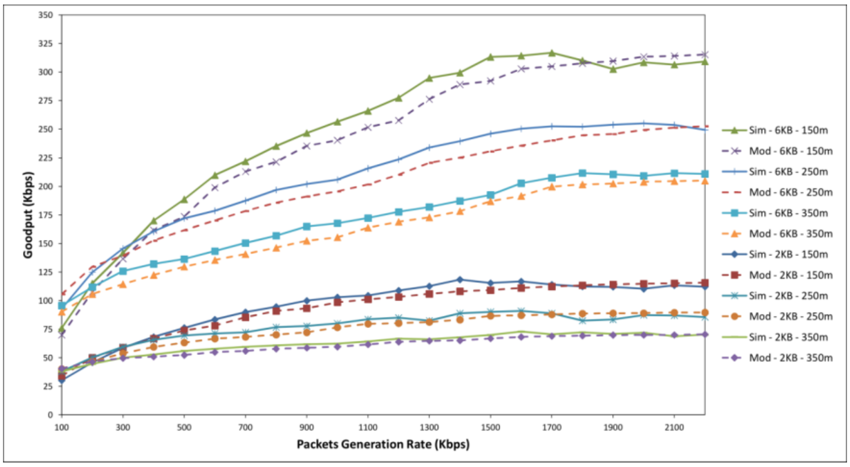

Fig. 5. Goodput versus packets generation rate for the BA method, in the case of packet size = 2kB or 6kB, R_{cs} = 150m, 250m or 350m, L = 600m, and R_{tx} = 150m

Two fundamental performance metrics are used to evaluate the proposed SRN models; goodput and end-to-end delay. The goodput is the number of data bits, not including protocol overhead and retransmitted bits, received correctly at a destination per unit time. Thus, goodput represents the application level throughput. End-to-end delay of data packets is the average time that a packet takes from the beginning of transiting the packet at a source node until the packet delivery to a destination. This includes delay time caused by buffering of data packets during route discovery, queuing at the interface queue for transmission at MAC layer, retransmission delays at MAC layer, and propagation and transfer delay times. In simulation, the throughput is computed by dividing the total number of received packets at all receivers by the simulation time, whereas end-to-end delay is obtained by summing up individual packet delays at all receivers and dividing the sum by the total number of received packets. The average goodput per source-destination pair and packet end-to-end delay for all simulation scenarios of the network are obtained by averaging over goodput of all source-destination pairs and end-to-end delay of all packets received by any destination, respectively.

For all simulation scenarios, all nodes move according to random waypoint mobility where the velocity of nodes is chosen uniformly from 0 to 20 m/s and the pause time is set to zero. For all mobility scenarios, nodes start to move at the start of the simulation and do not stop until the end of simulation. The source-destination pairs are chosen randomly over the network where Constant Bit Rate (CBR) traffic sources are used. The number of CBR sources is equal to the number of nodes where the destinations are randomly chosen. Identical mobility scenarios and traffic patterns are used across simulation scenarios to gather fair results. The simulation time is set to 1100s. The first 100s are discarded to be sure that the network has reached the steady state. All simulation results are obtained with 95% confidence interval. In Figures 10−20, solid lines refer to simulation results (labeled Sim), while dashed lines represent results of SRN models (labeled Mod).

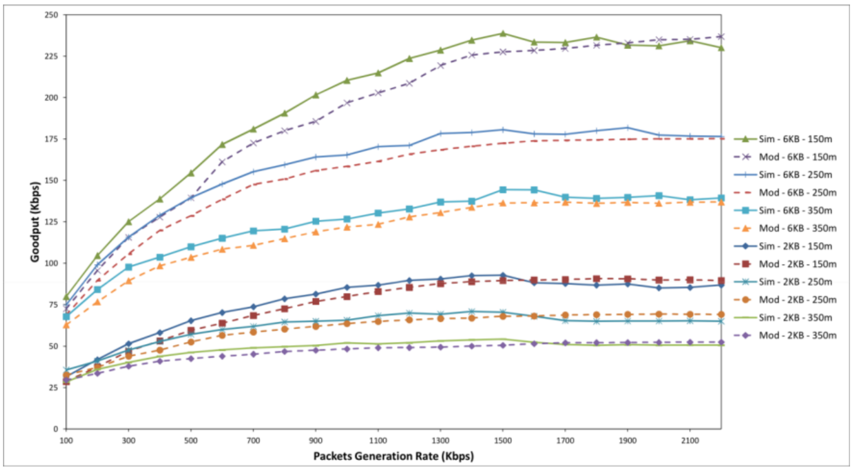

Fig. 6. Goodput versus packets generation rate for the RTS/CTS method, in the case of packet size = 2kB or 6kB, R_{cs} = 150m, 250m or 350m, L = 600m, and R_{tx} = 150m

To validate the proposed models, many network simulation scenarios are conducted. The settings of simulation scenarios consist of a network in a square area with side length L, where the number of nodes varies from 60 to 240, packets generation rate varies from 100 to 2200 kb/s, transmission range R_{tx} = 150 or 250m.

The first scenario is based on varying the packet generation rate in each source node from 100 to 2200 kb/s where the number of nodes N = 60, the size of network area is 600X600m, and transmission range is 150m. To investigate the effect of increasing the carrier sensing range and packet size on the performance of the network, R_{cs} is set to 150, 250, or 350m and the packet size is set to 2 or 6 kB. For this scenario, Figure 5 and 6 show the average goodput per source-destination pair verses increasing value for the packet generation rate for Basic Access (BA) and RTS/CTS (Request to Send/Clear to send) method [19], respectively.

As clear in Figure 5 and 6, in the case of light load conditions (small packet generation rate) the greater the packet generation rate the greater the goodput. However, in heavy load conditions, increasing the packet generation rate does not much affect on the goodput. This is because, in heavy load conditions when every node has a packet to send all the time, the contention to access the channel increases which increases the packets collision probability, interference between nodes, and buffer overflow. Thus, the number of packets losses increases that make any more increase in the packet generation rate has not a significant effect on goodput. Also, Figure 5 and 6 show the effect of increasing the carrier sensing range and packet size on the average goodput per source-destination pair under various channel traffic loads.

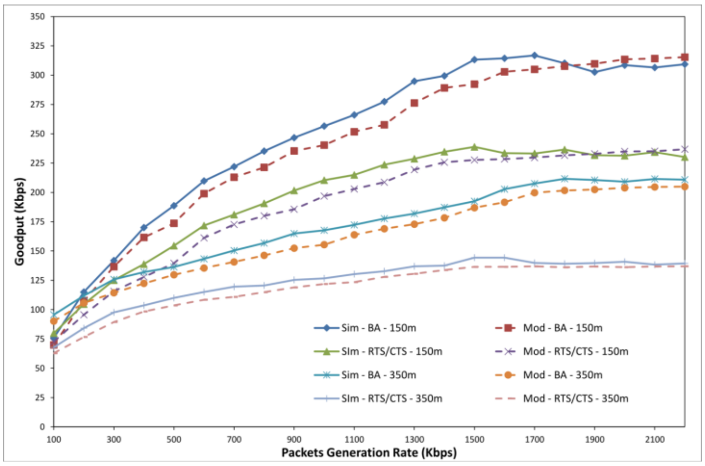

Fig. 7. Goodput versus packets generation rate for the BA and RTS/CTS methods, in the case of packet size = 6kB, R_{cs} = 150m or 350m, L = 600m, and R_{tx} = 150m

Increasing the carrier sensing range decreases the size of hidden area and number of hidden nodes N_H which consequently decreases the packet collision probability. However, the greater the carrier sensing range the greater the size of interference area and number of interfering nodes N_i which increase the packet collision probability and decreases the channel availability. Therefore, from Figure 5 and 6, it can be observed that a larger carrier sensing range results in a smaller goodput for both BA and RTS/CTS schemes.

Although increasing the packet size increases the packet collision probability due to hidden nodes and exponential backoff time per packet, it reduces the number of data packets sent per unit time that reduces the contention between nodes, and the packet collision probability due to interfering nodes. In addition, although the number of received packets per unit time in the case of lager packet size is smaller than that in the case of small packet size; the number of received bits per unit time is larger. Thus, as clear from Figure 10 and 11, the larger packet size improves the performance of the network for different carrier sensing ranges in both BA and RTS/CTS schemes.

As shown in Figure 10 and 11, with very light traffic load, increasing the packet size or carrier sensing range has not much significant effect on the performance of the network because the network load is very low, so most packet arrivals can be serviced successfully . In addition, with the same traffic load, with large packet size, it is to be noted that decreasing the carrier sensing range has more effect on the network goodput compared to small packet size. This is because, the smaller packet size increases interference and contention between nodes that make the goodput saturate fast with increasing the traffic load.

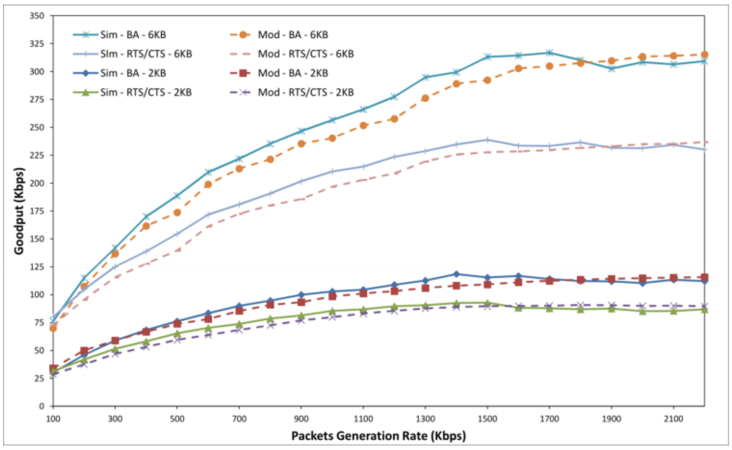

Fig. 8. Goodput versus packets generation rate for the BA and RTS/CTS methods, in the case of packet size = 2kB or 6kB, R_{cs} = 150m, L = 600m, and R_{tx} = 150m

In Figure 7 and 8, the comparison of the BA and RTS/CTS methods are made against the packet size and carrier sensing range. Figure 7 and 8 show the goodput versus the packet generation rate for BA and RTS/CTS method where in Figure 7 the packet size is 2 or 6 kB and R_{cs} = 150m , and in Figure 8 the packet size is 6 kB and R_{cs} = 150 or 350m. The figures reveal that in multi-hop ad hoc networks, in contrary to single hop ad hoc networks, BA method outperforms RTS/CTS method especially in heavy load and large packet size conditions. In the case of packet size is 6kB, increasing the carrier sensing range from 150m to 350m decreases the saturated goodput with 32.1% and 40.2% for BA and RTS/CTS methods, respectively and saturated goodpute for BA method is 32.4% higher than that for RTS/CTS method. This is because of the exposed terminal and blocking area problems for RTS/CTS.

To investigate the influence of the number of nodes on the end-to-end delay, Figure 9 shows the end-to-end delay versus increasing values of the number of nodes in the network (from 80 to 240 nodes) for BA method, where packet size = 2 kB, R_{cs} = 250 or 450m, L=1200, packets generation rate = 1000 kB/s, and Rtx = 250m. In Figure 9, it can be seen that for small number of nodes (less than180) the greater the number of nodes the greater the end-to-end delay because increasing number of nodes increases the collision probability and contention between nodes which increase the random exponential backoff time that increases the end-to-end delay. However, for large number of nodes, the end-to-end delay slightly increases with the increasing of the number of nodes because the system starts to saturate and becomes unable to serve any more packets.

As shown in Figures 5–9, the analytical results agree closely with simulation results. The difference between analytical and simulation results is due to the following approximations: (1) the time intervals of many events in the Data Link Layer Model, Network Layer Model, and Mobility Models, have been approximated to be exponentially distributed to be able to solve the proposed models analytically, (2) the approximate value for the number of neighbour nodes computed using the method introduced in [18], which is used to drive the number of hidden and interfering nodes, must be rounded to the nearest integer to be used to solve the models, and (3) the number of hops computed using the method introduced in [17] is usually overestimates the actual value and also it must be approximated to an integer number.

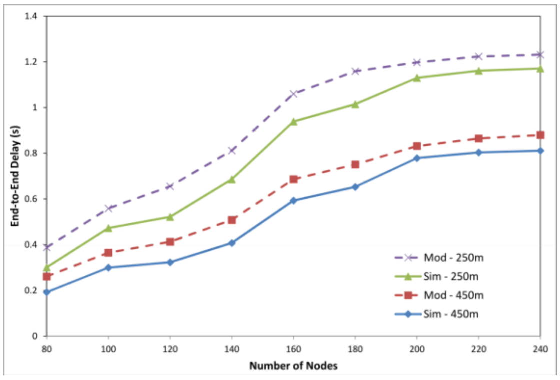

Fig. 9. End-to-end delay versus number of nodes for the BA method, in the case of packet size = 2kB, R_{cs} = 250m or 450, L = 1200m, and R_{tx} = 250

7 Conclusion

This work introduces an analytical framework for modelling MANETs that can be used to study the effect of various factors, such as communication range, density of nodes, random access behaviour, mobility patterns, and traffic load, on the performance indices such as packet end-to-end delay and network throughput, for performance analysis of MANETs. The proposed framework consists of five models; Path Analysis Model, Path Length Model, Data Link Layer Model, Network Layer Model, Transport Layer Model. To compute the required performance indices, such as delay and throughput, the three models are solved iteratively using the fixed point iteration technique. The proposed models are validated using extensive simulations.

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