

# An SRN Based Approach for Performance Evaluation of Network Layer in Mobile Ad hoc Networks

Meisam Yadollahzadeh Tabari\*

Department of Computer Engineering, Babol Branch, Islamic Azad University, Babol, Iran  
m\_tabari@baboliau.ac.ir

Ali.A Pouyan

Department of Computer & IT Engineering, Shahrood University of Technology, Shahrood, Iran  
apouyan@shahroodut.ac.ir

Received: 02/Aug/2018

Revised: 28/Feb/2018

Accepted: 19/May/2019

## Abstract

The application of mobile ad hoc networks in emergency and critical cases need a precise and formal performance evaluation of these networks. Traditional simulators like NS-2 and OPNET usually need considerable time for producing high-level performance metrics. Also, there is no theoretical background for mentioned simulators. In this research, we propose a framework for performance evaluation of mobile ad hoc networks. The presented framework points to the network layer of MANETs using Stochastic Reward Nets modeling tool as a variation of Generalized Stochastic Petri Nets. Based on the decomposition technique, it encompasses two separate models: one for analysis of data flowing process and the other for the modeling routing process. For verifying the presented model, an equivalence-based method is applied. The proposed model has been quantified by deriving two performances metrics as the Packet Delivery Ratio and End-to-end Delay. The results show the obtained values from the presented model well matched to the values generated from the NS-2 simulator with considerable shorter execution time.

**Keywords:** Mobile ad Hoc Network; Stochastic Reward Net; Performance Evaluation; Modeling.

## 1. Introduction

Mobile ad-hoc network (MANET) is a dynamic and scalable type of networks, which is free from the constraints of infrastructure. Mobile ad hoc networks are becoming very attractive and useful in many kinds of communication and networking applications. This is due to their efficiency, the simplicity of installation and use, low relative cost, and the flexibility provided by their dynamic infrastructure [1]. High performance is a fundamental goal in designing communication systems such as MANETs. Therefore, the performance evaluation of ad hoc networks is needed to compare various network architectures and protocols for their performance and to study both the effect of varying network parameters and the interaction between them [2,3]. It should be noted that most researches accomplished in the area of MANETs performance evaluation, utilized broadband of Discrete Event Simulators (DES) such as NS2 [4], OPNET [5], and GLOMOSIM [6]. The principal drawback of DES models is the time and resources needed to run such models for large realistic systems, especially when highly accurate results (i.e., narrow confidence intervals) are desired. In some cases, the results also differ from one simulator to another [7].

In addition to a large amount of computation time, it is challenging to study high-level typical specifications such as deadlock and concurrency in MANETs using DES. This is because the network simulators implement the network at a low level of abstraction and specifications at

a higher level cannot be supported well. Also, the most critical challenge that simulators face is the lack of any scientific and dependable modeling tool for depicting the correctness of the model [8]. Due to the advantages of quick construction, numerical analysis, and the ability of high-level performance evaluation, analytical modeling techniques, such as stochastic Petri nets, process algebra, and Markovian modeling have been used for the performance analysis of communication systems.

However, there are a few practical issues associated with analytical modeling tools that need addressing. First of all, modeling a real system requires a detailed concept of model formalism and the description of the system. Modeling tools usually emphasis on the stochastic behaviors of the investigated system. The probability of a packet reaching the destination, the likelihood of possible routes and the probability of a link failure are essential to be investigated. State space explosion problem is another major problem for modeling most of the complicated systems. An analytical model that is designed for a system should have two specific characteristics. First, it should be detailed enough that describes all the features and behaviors of the investigated system. Second, the model should not contain too many places, which increase the possibility of trapping in the state explosion problem.

Petri nets [10], and its variations like Stochastic Petri Net, Generalized Stochastic Petri Net, Colored Petri Net and etc.) as a known modeling tool that our work is based on, currently are widely used for modeling computer networks. In the definition, it includes places which can

\* Corresponding Author

point to the states of a system and tokens in each of them. The latter shows in which state a system is. Transitions along a pair of states represent system' dynamics, which cause the events. It allows characters like synchronization, concurrency, conflict, and mutual exclusion, which are features of communication protocols.

Compared to mathematical and Markov chains models, stochastic Petri nets models can easily be modified to cope with changes in a modeled system [21]. Also, the effectiveness of stochastic Petri nets has been demonstrated for modeling complex communications protocols. E.g., this formalism can deal with more than one data stream at a time, which offers excellent clarity for modeling distributed and parallel systems [11].

There are two distinct approaches for modeling a communication system with Petri net. In the first approach, each real network workstation bounds to a place in the Petri net model. Data flow between workstations is represented via a transition in Petri net. However, the main issue in this modeling approach is that the size (i.e., a high number of nodes), which usually leads to the state explosion problem that affects the performance of the proposed model

For evaluating the performance of a network with the Petri net model, it is recommended to apply a behavioral approach, rather than considering each network node as a Petri net place. In this approach, the number of nodes in the network does not affect the structure (i.e., size) of the proposed model. The model considers the functionality of each node and the interaction between them. In this paper, a representation of a behavioral framework for performance analysis of a mobile ad hoc network is proposed, which is based on the concept of decomposition using Stochastic Reward nets (SRN) with the emphasis on the behaviors of a node in the network layer

## 2. Related Works

There are not too many investigations, performed on performance evaluation of mobile ad hoc networks using analytical modeling. Most of the literature use analytical modeling tools like the Markovian model, and a few of them use Petri net. Here, we performed a brief review of some significant research conducted in this area.

In [12] the authors modeled all stations in an IEEE 802.11 based WLAN in one SPN model. The complete model was solved using simulation because it was too large for direct analytical analysis, due to state space explosion. Although the authors introduced two compact analytical models, they did not include some aspects of the IEEE 802.11 DCF protocol.

An approximate stochastic Petri net model for ad hoc network was presented in [13]. The proposed model tried to take advantage of the symmetry between nodes by describing the behavior of one node under a workload that is generated by the whole network. The SPN model consists of two subnets; incoming and outgoing subnets. The incoming subnet represents the processing of packets

received from other nodes, whereas the outgoing subnet models the transmission of packets generated in the current node. The model is so simple and seems not to be able to represent detailed characteristics of mobile ad hoc network. Xiong et al. [14] modeled and simulated ad hoc routing protocol using colored Petri Nets (CPNs). They used topology approximation mechanism to solve the problem of topology changes, which is an essential character of ad-hoc network. Ciardo et al. [15] modeled a scalable, high speed interconnect, which is a continuous hexagonal mesh-like wired network, with stochastic Petri Nets. They presented both exact and tractable approximate SPN model and compared it with simulation results based on CPNs. In [9] the authors perform a performance study of the distributed coordination function of 802.11 networks. They also illustrate the different classes of Petri Nets used for modeling network protocols and their robustness in modeling based formal methods. Their proposed model uses on Object-oriented Petri Nets for modeling IEEE 802.11b which considers Back-Off procedure and time synchronization. Then, performance analyses are evaluated by simulation for a dense wireless network and compared with other measurements approaches. Their model assessed using different metrics such as collision rates, the transition time. It does not mention how the performance metrics are derived from the model.

The authors in references [2,21] performed the most serious work for performance evaluation of mobile ad hoc network using Petri net. They proposed a general framework for performance analysis of MANET using SRN; a variation of GSPN. The model consists of two separate models for Data Link and network layer in addition to three mathematical models for spotting nodes behaviors in MANET. In their proposed SRN model for the network layer, there is no sign of routing protocol which is the most drawback of this job. Also, the model is only investigated on a single performance metric as Goodput.

In [7, 16] the authors present a node based Petri-net simulation model of a wireless mobile ad hoc network. They claim that the model covers all the fundamental aspects of the behavior of a network and uses a novel scheme of orientation-dependent (or sector-dependent) internode communication, with random states of links. Their proposed scheme enables the representation of reliability aspects of wireless communication, such as fading effects, interferences, the presence of obstacles and weather conditions. The simulation model was implemented in terms of a class of extended Petri nets to explicitly represent parallelism of events and processes in the WLAN as a distributed system. Because the presented model was a node-based model, it suffers from the state explosion problem along increasing in the number of nodes.

Also, in some investigations like [8,17], a class of Petri net is used the name as Fuzzy-Petri net, in which a type of fuzzy inference accomplished for firing each transition. In [8] the authors proposed a secure routing protocol for mobile ad hoc network based on fuzzy Petri modeling tool. In their presented approach, each network

node assigned to a place in the Petri net model. The link between any pair of nodes modeled by a transition. For each transition, four distinct fuzzy parameters are assigned to encounter the security levels of links and influenced nodes. The firing of each transition produces a security coefficient propagated along with the link from source to destination. For a network with a large number of nodes, this usually leads to the state explosion problem.

### 3. Stochastic Reward Nets

Basically, (SRN) is a kind of GSPN formalism [11]. GSPN is also innovated based on SPNs. SPN [10] is a class of Petri net in which, a firing delay is associated with each transition. Then, the transitions will fire after a probabilistic delay determined by a random variable. Stochastic Petri Nets were mainly proposed for quantitative analysis (performance evaluation) of the complex discrete event systems. A stochastic Petri net is defined with a five-tuple;  $SPN = (P, T, F, MO, A)$ , where

$P$  : is a set of states, called places.

$T$  : is a set of transitions.

$F$  : where  $F \subset (P \times T) \cup (T \times P)$  is a set of flow relations called "arcs" between places and transitions (and between transitions and places).

$MO$  : is the initial marking.

$A$  : is the array of firing rates,  $\lambda$  associated with the transitions. The firing rate, a random variable, can also be a function  $\lambda(M)$  of the current marking.

In Generalized Stochastic Petri net (GSPN), each transition has an associated firing time, which can be zero (immediate transition) or exponentially distributed with a parameter dependent on the marking (timed transition). Automatically, an immediate transition has priority over timed transitions. Timed transitions have exponential distribution firing time function with rate  $\lambda$ . Having a transition with a constant time  $T$ , the firing rate is set to  $1/T$ . Furthermore; GSPN uses the advantage of inhibitor arcs. This arc joints a transition to a place with a tiny circle sticking to place. For firing this transition, no token should be held in directed place. This simple ability causes a produced model more powerful with a fewer number of places and transitions. SRNs as a superset of GSPNs increases the modeling power of the GSPN by adding guard functions, marking dependent arc multiplicities, general transition priorities, and reward rates at the net level. A guard function is a Boolean function associated with a transition. Whenever the transition satisfies all the input and inhibitor conditions in a marking  $M$ , the guard is evaluated. The transition is considered enabled only if the guard function evaluates to true. Marking dependent arc multiplicities allow either the number of tokens required for the transition to be enabled, or the number of tokens removed from the input place, or the number of tokens placed in an output place to be a function of the current marking of the PN. Such arcs are called variable cardinality arcs. As the simplest way, in

each SRN model, a set of performance metrics can be derived using a combination of specifications related to transitions and places. For transitions, characteristics like, Throughput: which is the number of times the transition fires per time unit and Probability of firing is used. Average marking and Steady-state distribution of tokens are also used for spotting characteristics of places. The combination of evaluation tools directly depends on the modeled system and may vary from one system to another. Each graphical SRN model also has structurally algebraic properties known as P-Invariant and T-Invariant. Those could usually represent high-level behaviors of a system which is modeled by Petri net [10, 11]

### 4. Model Description

The topology of MANET is highly dynamic because of frequent mobility of nodes. Thus, there are many inter-dependent parameters, mechanisms, and phenomena which should be considered in the presented model. Two requirements should be fulfilled in advance to present an approach for the modeling and analysis of large-scale ad hoc network systems. First, the model should be elaborated in detail to express all network characteristics that have a significant impact on its performance. This leads to a model with a large number of Places and Transitions which may trap in the state explosion problem. Second, it should be simple enough to be scalable, analyzable and also recognizable. It is clear that these two requirements are contradictory. Therefore, the approximate model presented based on the idea of decomposition [28]. In this technique, the model decomposes into two or more sub-models that are solved iteratively. The approximated model should work with a large number of nodes and basically describes the behavior of one node under a given workload that is generated by the whole ad hoc network. The approximated model covers all necessary activities from incoming and outgoing subnets representing different behavior of nodes from the perspective of a single node in the network layer. Despite general network parameters, routing protocol has a significant impact on the generated model.

Regarding AODV as the selected routing protocol, there are two distinct flows in a network. A flow for finding a path from the source node to the destination is known as the routing process and a kind of flow for delivering the data packet to a destination known as the data flow process. These two processes differ in a way that the latter uses a ready route that is produced by the first model. This inspired us to decompose the overall model into two separate models for data flow and routing process. Those are presented in figures 1&3. In both models, the places are the mappings of nodes' states in a network. Timed transitions stand for the required time for performing a task in the network. As an example, the time needed for delivering a packet from a node to its neighbor is represented by a timed transition.

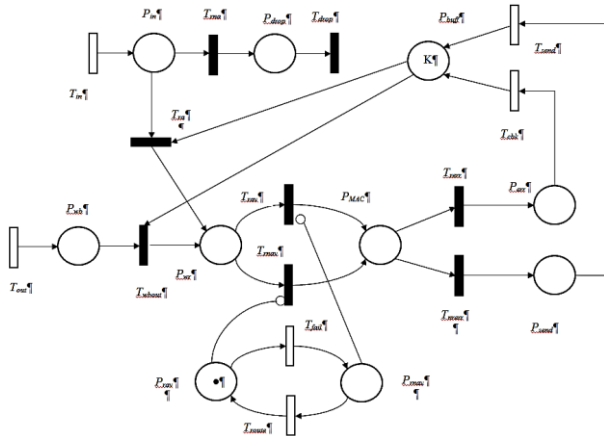


Fig. 1. SRN model for network data flow inspired by [2]

Immediate transitions are also used for declaring a conflict or choice in network behavior. The probabilities associated with these conflict transitions, a well-defined probability function should be assigned to each transition which is deduced from network behaviors.

A firing rate of transition or its probability can be obtained from network standards specifications or mathematical calculations. Sub-sections 4-1 and 4-2 give precise and detailed information for both models with the values associated with parameters.

#### 4.1 SRN Model for Modeling Network Data Flow

As it is illustrated in Figure 1, the model which is designed for data flow process encompasses two sections, inspired by [2] the two mentioned sections considered for spotting incoming and out-coming data flows.

Out-coming flow directs to the actions performed for generating a packet in a node and delivering it to the destination. This flow started with the transition  $T_{out}$  in figure 1. The firing rate of this transition equals  $\lambda$  which is a network parameter, and it is the same as the packet generation rate in a network. Packets are usually generated using CBR traffic, and its rate can be interpreted as  $\lambda$ . A generated packet needs to buffer space for starting its routing process.

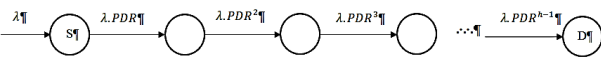


Fig. 2. The input  $\lambda$  data traffic rate that is produced from the source node along the path toward the destination

This is shown using place  $P_{wb}$  indicating packets which are waiting for occupying a buffer in the current node for flowing their data.

If there is at least one token from  $K$  supposed buffer space in network layer standard, this transition would be fired and flows the token to the place  $P_{wr}$ . Due to modeling issues, we investigate a network with established routes and ignored the first routing process which is needed at the beginning of a network lifetime. For an established route, there is a probability of route failure which is due to nodes movements or other issues. This is represented by  $T_{fail}$  which its firing rate is deduced from [18]. The authors in this research proposed a Petri net model for path connection availability for

multihop ad hoc network. They investigated the effects of transmission range, network size, data transmission rate, and routing protocol. After occurrence a failure, a new routing process is needed which is shown using transition  $T_{route}$ . The required time for this transition is derived from the routing process model introduced in section 4 (B).

Along specifying route toward the destination and completing the routing process, the generated packet should be sent to the next node through the Data Link layer.

A token, in this case, injected to the place  $P_{MAC}$  which indicates that the MAC layer is ready for transmitting the data packet to the next ongoing node. IEEE 802.11 DCF as a known Data Link protocol is responsible for the nodes coordination in this layer. Despite, the advanced technique which is used in this protocol, a collision may occur for sending packets through a common channel in a neighbor area. The probability associated for this probability which is shown using the choice ( $T_{err}-T_{nerr}$ ) is derived from an investigation performed in [21]. Also, the required time for transitions  $T_{send}$  and  $T_{CBK}$  which stand as the time needed for sending a data packet and sending Call Back error is also derived from this research. For incoming section, in AODV routing protocol, if a node receives a data packet which has no unexpired route for, it drops the Packet immediately. Otherwise, it delivers the packet to the MAC layer for sending the received packet to the next hop node in route toward the destination. The two possible outcomes are represented with a choice structure using transitions  $T_{ra}$  and  $T_{rna}$ . As stated, in our presented model it is supposed that all routes are initialized. Then,  $T_{rna}$  shows the event that a route is disturbed because of nodes movements or other conditions which may occur in a route failure.

The probability associated with  $T_{rna}$  is derived from our previous study in [3]. Then  $T_{ra}$  would be as  $1 - T_{rna}$ . As another parameter, the firing rate of transition  $T_{in}$  should be defined. This transition points to the data traffic which is forwarded toward a node for sending it to the next consequent node in an established route. The firing rate of this transition has direct relevance to the number of source nodes ( $M_s$ ), their produced data traffic rate ( $\lambda$ ) and the Packet Delivery Ratio ( $PDR$ ) of each node in a route.

The obtained value is averaged entirely over the whole number of nodes in the network. The input  $\lambda$  data traffic rate that is produced from the source node is multiplied over the  $PDR$  value of each node along the path from the source node to the destination. Figure 2 illustrates the process. The overall expression for rate( $T_{in}$ ) expressed via equation 1 using the mathematical calculations reported in [2]. The  $PDR$  value used in this equation calculated via equation 2.  $h$  points to the value of hop-count that its value produced from the instruction reported in [27].  $Thr(T_x)$  points to the throughput value of transition  $T_x$ .

$$rate(T_{in}) = \frac{M_s \cdot \lambda \cdot (PDR + PDR^2 + \dots + PDR^{h-1})}{M} \tag{1}$$

$$PDR = \frac{Thr(T_{send})}{Thr(T_{out}) + (Thr(T_{in}) \times Pr(T_{ra}))} \tag{2}$$

## 4.2 SRN Model for the Modeling Routing Process

For this section, the behavior of AODV routing protocol is modeled for finding a route to the destination. In AODV routing protocol, the routing process initiates through the propagation of RREQ messages to the neighbor's nodes with a TTL number indicating the dissemination range of such RREQ propagation. This is decremented by one for each transmission of RREQ from one node to another. RREQ passes through nodes, in order to reach the destination. This process terminated by reaching a node has a valid route toward destination. The whole process is modeled in Figure 2. As it can be seen in this figure  $T_{RREQ}$ , initiates the routing process. After that, it puts the TTL number of tokens to the place  $P_{TTL}$ . Firing of transition  $T_{TTL}$  also, decrement TTL count by one and sends the token to the place  $P_{wr2}$  for determining path availability through routing table of the next nodes which are in one-hop communication of the current node.

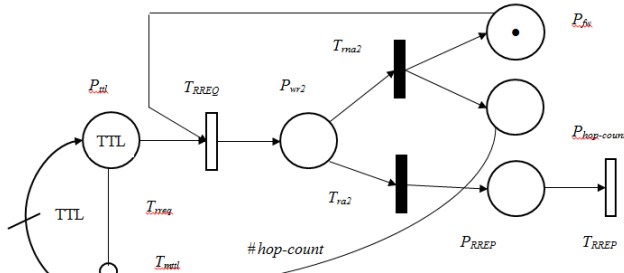


Fig. 3. SRN model for routing process

According to [23] Supposing Random Way Point (RWP) as our selected mobility model, and totally  $M$  number of nodes communicating in a network, the number of neighbor ( $N$ ) in a neighbor area would be as equation 3.

$$N = N_{ra}^{RWP} = \frac{r_a^2}{3} ((4 - 2P_p + P_p^2) - \frac{4}{\pi} P_p^2 r_a - 3(1 - P_p) r_a^2) \times \frac{\pi}{A} \times M \quad (3)$$

In this equation,  $r_a$  points to the transmission range of each node,  $A$  is network area, and  $P_p$  denotes to the probability that a node in a specific time be in its pause time duration and calculated as  $P_p = \frac{\tau_p}{\tau_p + E(T)}$ .

In that  $r_a$  points to the transmission range of each node,  $A$  is network area, and  $P_p$  denotes to the probability that a node in a specific time be in its pause time duration and calculated as  $P_p = \frac{\tau_p}{\tau_p + E(T)}$ .

Where  $E(T)$  is also points to the expected time between two waypoints and estimated using the method introduced in [24] as equation 4.  $a$  stands for the network area dimension.  $V_{max}$  and  $V_{min}$  points to the nodes minimum and maximum speed, respectively.  $\tau_p$  is also the ordinal pause time; the nodes stay in a position before moving to a new location. If all of the neighbor nodes act legitimately, there is a possibility that one or more of them have a route toward the destination and send back legitimate RREP. This is also represented by  $T_{ra}$  and  $T_{rna}$ . If one of the neighbor nodes has a valid route to the

destination, the transition  $T_{ra}$  would be fired. This probability has direct relevance to the routing table size of each node over the whole number of nodes. Note that each entry in a routing table points to the next hop node in a path along to the destination. Average routing table size is derived from an investigation performed in [24]. Form this explanation  $Pr(T_{rna2})$  expressed as equation 5.

$$Pr(T_{rna2}) = \left(1 - \frac{(RT\_Size)}{M}\right)^N \quad (5)$$

$$Pr(T_{rna2}) = 1 - Pr(T_{rna}).$$

Place  $P_{hop-count}$  preserved for counting average the number of hops toward destination. Also, a guard function specified to transition  $T_{ttl}$  indicating that it would not fire nevertheless any number of tokens remained in places  $P_{wr2}$ ,  $P_{legitimate}$ ,  $P_{fw}$  and  $P_{RREP}$ . The time associated with transition  $T_{RREQ}$  equals to the time needed for sending RREQ packet via a common broadcast channel. IEEE 802.11 DCF usually uses 2-handshake (BA) method for sending control packet toward the channel. In this approach, a node simply sends its low size data or control packet after a DIFS interval of sensing the channel free. Along receiving a packet from sender, the receiver node sends back an ACK frame to announce its successful reception after a SIFS interval of sensing the channel free. Then,

$$Time(T_{RREQ}) = \tau_{DIFS} + \tau_{SIFS} + \tau_{ACK} + \tau_{control\ packet} \quad (6)$$

$\tau_x$  equals to the time needed for sending packet  $x$  via broadcasting in common channel. Also, the time needed for firing  $T_{RREP}$  equals to the time needed for sending back RREP packet toward the node that missed the route. This is formulated as equation 7.  $\#(P_{hop-count})$  stands for the average number of tokens in place  $P_{hop-count}$ .

$$Time(T_{RREP}) = (\tau_{DIFS} + \tau_{SIFS} + \tau_{ACK} + \tau_{control\ packet}) \times \#(P_{hop-count}) \quad (7)$$

The standard times  $\tau_x$  which are used in equations 3,4 derived from the Data Link layer standard [21]. The time required for firing  $T_{route}$  in network data flow model which depends on the routing process model derived using equation 8. In this equation TTL is the assigned value for Time To Live,  $\#(P_{ttl})$  is the average number of tokens in place  $P_{ttl}$ ,  $Thr(T_{ttl})$  stands for firing throughput for the transition  $T_{ttl}$ .  $T_{RREP}$  is also the taken time for the sending a single RREP message.

$$Time(T_{route}) = \frac{TTL - \#(P_{ttl})}{Thr(T_{ttl})} + T_{RREP}. \quad (8)$$

Table 1. Parameters value related to equations 3, 4

Parameter	value	Parameter	value
$T_{DIFS}$	50 $\mu s$	$T_{CTS}$	$\frac{(112 + phH)\ bit}{1\ Mbps}$
$T_{SIFS}$	10 $\mu s$	$T_{ACK}$	$\frac{(112 + phH)\ bit}{1\ Mbps}$
$T_{RTS}$	$\frac{(160 + phH^*)\ bit}{1\ Mbps}$	$T_{Data}$	$\frac{(Data + phH)\ bit}{2\ Mbps}$

\* Physical Header =192 bit

### 5. Performance Evaluation & Model Validation

For measuring performance metrics and showing the correctness of our model, an equivalence-based method is used. For doing that, two performance metrics are quantified in both NS-2 SPNP PIPE simulator. SPNP [19] is an analytical environment specifically for modeling SRN. It includes all required components with all methods for analyzing an SRN model. *PDR* and *End-to-End delay* are the two metrics which are used. By definition *End-to-End delay* refers to the time needed for sending a packet from source node to the destination. It includes three different times. 1) The initial time required for the routing process, 2) The time required for delivering the packet from source node to the next 1-hop communication in the path. 3) The time required for delivering a packet from an intermediate node to the next one as it reaches the destination. According to *h* hop count from the source node to the destination, the latter time will be multiplied to *h*. Then, the overall expression for the End-to-End delay metric is as equation 9. In that, the expression  $Time(T_{route})$  expressed using equation 8 and the two latter times, is represented using *little law*.

$$End\ to\ End\ Delay = [Time(T_{route})] + \left[ \frac{\#(P_{in}) \times Pr(T_{ra})}{Thr(T_{send})} \right] + \left[ \frac{\#(P_{wb})}{Thr(T_{send})} \times h - 1 \right] \tag{9}$$

Also, the **PDR** is defined as the percentage of the number of packets sent by a constant bit rate from a sources node per the number of received packets by sink/destination [25,26]. This performance evaluation parameter measures the delivery reliability, effectiveness,

and efficiency of the routing protocol. The expression for this metric is expressed in equation 2 (previous section).

#### 5.1 Implementation

In the implementation phase, in a specific NS-2 scenario, mobile nodes were chosen for moving in an area as 1000 × 1000 dimension using the random waypoints mobility model. They move with a speed that is uniformly selected from 0 to 20 in a network with 2Mb bandwidth. The pause time ( $\tau_p$ ) is set to 120 (s). Each node has the transmission range of 250 m and carrier sensing range of 550 m. Network CBR is used to generate data packets. Four different packet generation rates ( $\lambda$ ) investigated as 300 kbps, 600 kbps, 900 kbps, and 1.2 Mbps. Each metric is also investigated for 50, 60, 70, 80, 90 and 100 numbers of nodes. The Routing protocol is set to AODV as our assumption. Network CBR is used to generate data packets. For each traffic generation rate ( $\lambda$ ), the CBR amount is adjusted to match this value. The required time for computing equations 6,7 which is related to the firing rate of transitions  $T_{RREQ}$  and  $T_{RREP}$  is also derived from the Data Link Layer standard. The assigned times for the transitions  $T_{DIFS}$ ,  $T_{SIFS}$ ,  $T_{RTS}$ ,  $T_{CTS}$ ,  $T_{ACK}$ ,  $T_{DATA}$  which are used in equations 6,7 are elaborated in Table 1. Also, the K value as a parameter of the SRN model which direct to the number of free buffer in a node is set to 64 which is a standard value. For NS-2 each of metrics value averaged from 10 runs of each scenario. This is because some considerable fluctuations have been seen in each run of a specific scenario in this environment. Figures 4 and 5 show obtained values for the performance metrics End-to-End delay and *PDR* respectively. The obtained values plotted versus number of nodes for both NS-2 and presented SRN model.

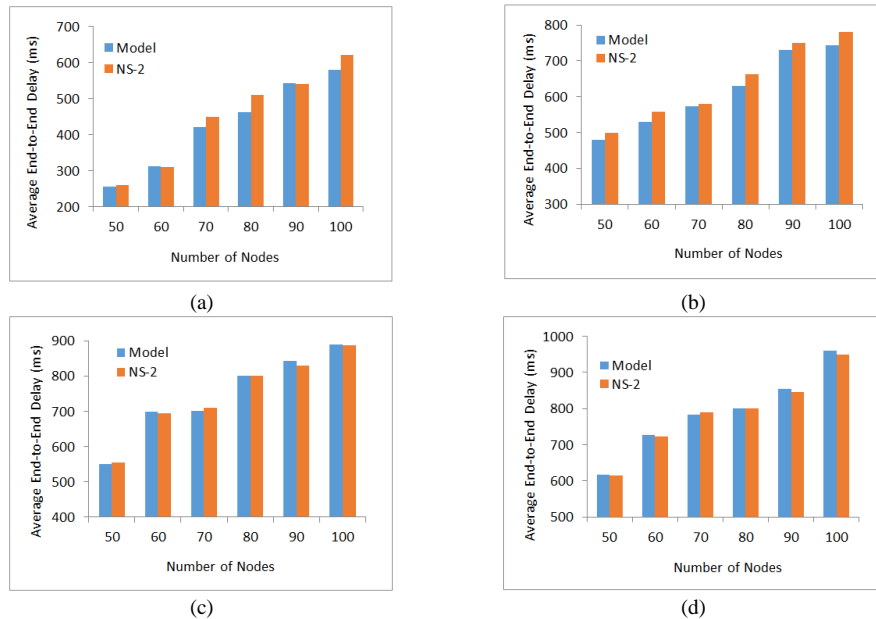


Fig. 4. End-to-End delay versus number of nodes using NS-2 and model.  
 $\lambda =$  a) 300 Kbps b) 600 Kbps c) 900 Kbps d) 1.2 Mbps

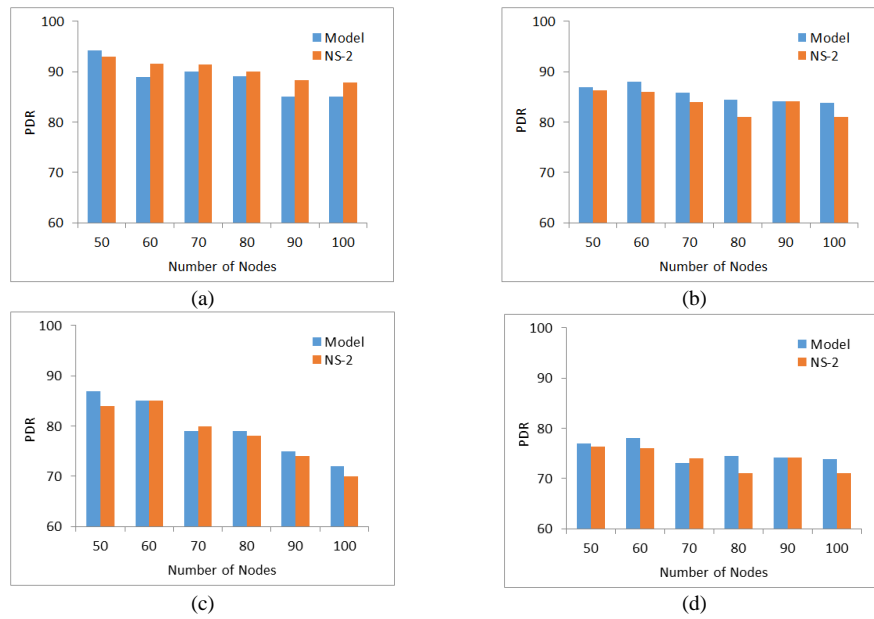


Fig. 5. PDR versus number of nodes using NS-2 and SRN model.  
 $\lambda =$  a) 300 Kbps b) 600 Kbps c) 900 Kbps d) 1.2 Mbps

As it is clear, for all metrics the values obtained from the proposed SRN model is well matched to the value obtained from NS-2. This can prove the correctness of the presented model and analysis.

As shown in figure 4, increasing in the number of nodes leads to higher waiting time for the nodes in order to transmit their data packets. Through preparing the results it is observed that increasing in the number of nodes, raises the probability of failure for forwarding a packet through the Data Link layer. Also rising the number of nodes makes more firing rate for the transition  $T_{fail}$  which in turn cause more firing count for the transition  $T_{route}$  in the model. Unlike, this phenomenon leads to a shorter firing time for the transition  $T_{route}$ . This is because increasing in the number of nodes leads to the more number of nodes in a neighboring area which raises the chance for a requester node to get RREP from one of its neighbors. This probability is shown using the choice structure ( $T_{ra2} - T_{ma2}$ ) in the routing process model. Totally, the results show that the mentioned outcomes lead to a more End-to-End delay by increasing the number of nodes. Packet generation rate ( $\lambda$ ) has a similar effect on this metric. This increase in the packet generation rate in the Data Link Layer which leads to the more firing probability for the transition  $T_{err}$ . This also increases the firing rate for the transitions  $T_{in}$  and  $T_{out}$  which accumulate more tokens in place  $T_{MAC}$ . As our investigation, it does not effect on firing time of transition  $T_{route}$ .

As it is clear in Figure 5 it can be seen a decreasing trend for the PDR value, in terms of increasing in the number of nodes. For this metric, also the two distinct values obtained from SRN and NS-2 is jointly agreed together. Like previous, raising the number of nodes and packet generation rate, raises the probability of failure for forwarding a packet through the Data Link layer. This makes more firing rate for the transition  $T_{fail}$  and raises the probability value for transition  $T_{err}$ . This gives lower firing throughput for the transition  $T_{send}$  which reduces PDR value totally.

As our major claim about the spanned time for deriving performance metrics from the SRN model in comparison to the NS-2 network simulator, a brief discussion presented here about how long those are taken. For the SRN model, the solution time (the time needed to generate the Markov chains model and computing the required performance metrics) for both presented models is highly related to the number of generated states. The number of states of the *data flowing process model* is highly depended on firing rates of the transitions  $T_{in}$ ,  $T_{out}$ , and  $T_{fail}$ . In its worst case, it doesn't hit 30 (s). On the other hand, increasing in the number of nodes, grows the solving time in NS-2 simulator, exponentially. In some cases, it takes about one hour for generating a result from NS-2 network simulator.

## 6. Conclusions

In this research, an SRN model presented for performance evaluation of network layer in mobile ad hoc networks. The model encompasses two separate models. One model stands for data flow process and another for the routing process which is based on AODV routing protocol. For verifying the correctness of the presented model, an equivalence-based method used. For this matter, two known performance metrics as End-to-End Delay and PDR are derived from the model and compared to the values that are obtained from NS-2. The results showed that the values obtained from the presented SRN model well matched to the values driven from NS-2 results. This can show the correctness of the presented model. Spanned time was quite negligible for presented SRN model compared to the time needed for NS-2. The presented SRN model can be used and expanded more as a general framework for any analysis and extracting MANET behaviors in the future.

## References

- [1] Tabari MY, Hassanpour H, Pouyan A, Saleki S. Proposing a light weight semi-distributed IDS for mobile ad-hoc network based on nodes' mode. In 6th International Symposium on Telecommunications (IST) 2012 Nov 6 (pp. 948-953). IEEE.
- [2] Younes O, Thomas N. Modelling and performance analysis of multi-hop ad hoc networks. *Simulation Modelling Practice and Theory*. 2013 Nov 1;38:69-97.
- [3] Pouyan A, Yadollahzadeh Tabari M. Estimating reliability in mobile ad-hoc networks based on Monte Carlo simulation. *International Journal of Engineering*. 2014 Jan 21;7(5):739-46.
- [4] "The Network Simulator ns2," available at <http://www.isi.edu/nsnam/ns/>.
- [5] "OPNET Modeler," available at <http://www.opnet.com>.
- [6] Zeng X, Bagrodia R, Gerla M. GloMoSim: a library for parallel simulation of large-scale wireless networks. In Proceedings. Twelfth Workshop on Parallel and Distributed Simulation PADS'98 (Cat. No. 98TB100233) 1998 May 26 (pp. 154-161). IEEE.
- [7] Kostin A, Oz G, Haci H. Performance study of a wireless mobile ad hoc network with orientation - dependent internode communication scheme. *International Journal of Communication Systems*. 2014 Feb;27(2):322-40.
- [8] Pouyan AA, Yadollahzadeh Tabari M. FPN - SAODV: using fuzzy petri nets for securing AODV routing protocol in mobile Ad hoc network. *International Journal of Communication Systems*. 2017 Jan 10;30(1):e2935.
- [9] Masri A, Bourdeaud'Huy T, Toguyeni A. Performance analysis of IEEE 802.11 b wireless networks with object oriented Petri nets. *Electronic Notes in Theoretical Computer Science*. 2009 Jul 13;242(2):73-85.
- [10] Marsan MA, Balbo G, Conte G, Donatelli S, Franceschinis G. Modelling with generalized stochastic Petri nets. John Wiley & Sons, Inc.; 1994 Oct 1.
- [11] Tang Y, Chen L, He KT, Jing N. SRN: an extended Petri-net-based workflow model for Web service composition. In Proceedings. IEEE International Conference on Web Services, 2004. 2004 Jul 6 (pp. 591-599). IEEE.
- [12] German R, Heindl A. Performance evaluation of IEEE 802.11 wireless LANs with stochastic Petri nets. In Proceedings 8th International Workshop on Petri Nets and Performance Models (Cat. No. PR00331) 1999 (pp. 44-53). IEEE.
- [13] Zhang C, Zhou M. A stochastic Petri net-approach to modeling and analysis of ad hoc network. In International Conference on Information Technology: Research and Education, 2003. Proceedings. ITRE2003. 2003 Aug 11 (pp. 152-156). IEEE.
- [14] Xiong C, Murata T, Tsai J. Modeling and simulation of routing protocol for mobile ad hoc networks using colored petri nets. In Proceedings of the conference on Application and theory of petri nets: formal methods in software engineering and defence systems-Volume 12 2002 Jun 1 (pp. 145-153). Australian Computer Society, Inc.
- [15] Ciardo G, Cherkasova L, Kotov V, Rokicki T. Modeling a scalable high-speed interconnect with stochastic Petri nets. In Proceedings 6th International Workshop on Petri Nets and Performance Models 1995 Oct 3 (pp. 83-92). IEEE.
- [16] Kostin A, Oz G, Haci H. Performance study of a wireless mobile ad hoc network with orientation-dependent internode communication links. In 2009 24th International Symposium on Computer and Information Sciences 2009 Sep 14 (pp. 316-321). IEEE.
- [17] Chiang TC, Tai CF, Hou TW. A knowledge-based inference multicast protocol using adaptive fuzzy Petri nets. *Expert Systems with Applications*. 2009 May 1;36(4):8115-23.
- [18] Younes O, Thomas N. A path connection availability model for MANETs with random waypoint mobility. In Computer Performance Engineering 2012 Jul 30 (pp. 111-126). Springer, Berlin, Heidelberg.
- [19] Ciardo G, Muppala J, Trivedi K. SPNP: stochastic Petri net package. In Proceedings of the Third International Workshop on Petri Nets and Performance Models, PNP89 1989 Dec 11 (pp. 142-151). IEEE.
- [20] Younes O, Thomas N. An SRN model of the IEEE 802.11 DCF MAC protocol in multi-hop ad hoc networks with hidden nodes. *The Computer Journal*. 2011 Jun;54(6):875-93.
- [21] Yadollahzadeh Tabari M, Pouyan AA. Misbehavior analysis of IEEE 802.11 MAC layer in mobile ad hoc network using stochastic reward nets. *International Journal of Communication Systems*. 2017 Nov 10;30(16):e3385.
- [22] Soltani MD, Purwita AA, Zeng Z, Haas H, Safari M. Modeling the random orientation of mobile devices: Measurement, analysis and LiFi use case. *IEEE Transactions on Communications*. 2019 Mar;67(3):2157-72.
- [23] Bettstetter C. On the connectivity of ad hoc networks. *The computer journal*. 2004 Jan 1;47(4):432-47.
- [24] Xu J. On the fundamental tradeoffs between routing table size and network diameter in peer-to-peer networks. In IEEE INFOCOM 2003. Twenty-second Annual Joint Conference of the IEEE Computer and Communications Societies (IEEE Cat. No. 03CH37428) 2003 Mar 30 (Vol. 3, pp. 2177-2187). IEEE.
- [25] Hu X, Jiao L, Li Z. Modelling and performance analysis of IEEE 802.11 DCF using coloured Petri nets. *The Computer Journal*. 2016 Oct; 59(10):1563-80.
- [26] Erbas F, Kyamakya K, Jobmann K. Modelling and performance analysis of a novel position-based reliable unicast and multicast routing method using coloured Petri nets. In 2003 IEEE 58th Vehicular Technology Conference. VTC 2003-Fall (IEEE Cat. No. 03CH37484) 2003 Oct 6 (Vol. 5, pp. 3099-3104). IEEE.
- [27] Hieu TD, Choi SG. Simulation modeling and analysis of the hop count distribution in cognitive radio ad-hoc networks with shadow fading. *Simulation Modelling Practice and Theory*. 2016 Dec 1;69:43-54.
- [28] Ciardo G, Trivedi KS. A decomposition approach for stochastic Petri net models. In Proceedings of the Fourth International Workshop on Petri Nets and Performance Models PNP91 1991 Dec 2 (pp. 74-83). IEEE.

**Meisam Yadollahzadeh Tabari:** Received his Ph.D. degree in Artificial intelligence from Shahrood University of technology in 2016. He also received his M.Sc. and B.Sc. degree from Arak and Iran University of science, respectively. Now he is Faculty member in the department of computer engineering of Islamic Azad university-Babol branch. His research interests include Performance evaluation, Analytical modeling and Data mining.

**Ali.A pouyan:** Dr. Ali A. Pouyan is currently with the department of computer engineering in Shahrood University of technology, Iran. He received his Ph.D. in computer engineering from Swinburne University of Technology, Melbourne, Australia. He completed his post-doctoral program at Industrial Research Institute Swinburne (IRIS) in control software. Dr. Pouyan published several research articles in international journal and conference papers. He also collaborated in several national industrial projects including telemetry of vital human signals, GSM platform, and designing and implementation of a software package for location problem. He is currently engaged in several research projects, including Petri net modeling, wireless networks, smart home, machine learning, and signal processing.