Fundamental Features of Ad Hoc Networks' Simulations

TAPIO FRANTTI
VTT Technical Research Centre of Finland
Kaitoväylä 1, FIN-90571 Oulu
FINLAND

MIRJAMI TARAMAA
VTT Technical Research Centre of Finland
Kaitoväylä 1, FIN-90571 Oulu
FINLAND

ods in description
of complicated real-world phenomenons. There are multiple reasons for that such as dramatic increase in processing power and significant decrease of price of the computing systems and the fact that the probability theory is a well-known tool for presentation and processing of stochastic information. As a primary aim, in this article is described fundamental stochastic features of the ad hoc network simulations. Especially, a concept of convergence time of simulation models is considered. It refers to the minimum simulation time required for the reliable results. Its practical numerical model-based evaluation is defined by example simulations. Ad hoc network models considered here are event based discrete time models, which utilize Markov chain theory for the definition of state transitions and Monte Carlo random sampling method for the definition of events probabilities and duration times of them. Numerous reported case studies of the network simulations do not contain any information about the convergence time of the model. In some publications results are achieved by very short simulation times spanning from a few seconds only to tens of seconds. Moreover, the same simulation times are used for different sizes of networks. However, the convergence time even for a moderate size of ad hoc networks, such as 10 nodes, may be thousands of seconds and it increases as a function of nodes as will be shown in this paper. The secondary aim of the paper is to optimize IEEE 802.11b AODV (Ad hoc On demand Distance Vector) based network throughput by parameters optimization. In simulations, it was noticed that RTS/CTS (Ready to Send/Clear to Send) threshold initiation and active route timeout parameters had significant influence to the overall throughput in small networks.

Key–Words: ad hoc networks, stochastic simulation, convergence time

1 Introduction

Ad hoc networks are a multihop[1] wireless, usually local area, networks consisting of a radio-equipped mobile or stationary nodes with networking capability. They are characterized as a self-organizing network, where nodes can form a temporary network without any pre-established network infrastructure or centralized control such as access points and base stations. Transmitting nodes are required themselves to compute routes to destination nodes and transmit routing information to neighboring nodes according to some routing protocol. Routing protocols can be categorized to *reactive* and *proactive* protocols. Reactive routing protocols define the most suitable route from source to destination when required, *i.e.*, reactively. Proactive routing protocols update the topological information of the network continuously, *i.e.*, periodically by time being rather than waiting to respond. In addition of the reactive and proactive routing protocols, in the literature has been presented numerous *hybrid* protocols including features from the reactive and proactive protocols.

Hence, due to routing requirement each node is designed to serve also as an intermediate node or router. This is the main difference between ad hoc networks and other kind of communication networks. As a result, ad hoc networks can be defined as a distributed multihop networks with time-varying topology, in which nodes can move around on network's coverage area and leave or enter the network at arbitrary time.

For the ad hoc networks research, stochastic simulation is widely used method. It can yield immense benefits to researchers because it lets them to draw appropriate conclusions before major investments are made. The validity of the conclusions naturally depends greatly on the accuracy of the model and the correct use of it.

In simulation techniques, an ad hoc network can be modelled to an arbitrary level of detail and the model parametrization is a more straightforward task. In many cases simulation also is the only possible choice for performance evaluation of ad hoc networks

[1]Multihop concept means the routing of traffi c from a source node to a destination node via intermediate nodes.

due to size, complexity and distributed calculation of the network state transitions and events.

In this article is described fundamental stochastic features of ad hoc network simulation models. Especially, the concept of convergence time and its effects are considered. Practical model-based evaluation of the convergence time is defined by example simulations. The aims of the paper are to clarify the concept of convergence time and it's significant role for reliable results and to optimize IEEE 802.11b AODV (Ad hoc On demand Distance Vector) based network throughput by parameters optimization. Network models considered here are event based discrete time models, which utilize Markov chain theory for state transitions and Monte Carlo method for duration times of events.

2 Throughput of AODV networks

An AODV (Ad Hoc On Demand Distance Vector) ad hoc network simulation model developed and considered here consisted of 10 active nodes. Radio technology, physical and link layers of the ad hoc network were modelled according to the IEEE 802.11b WLAN (Wireless Local Area Network) standard with system capacity of 11 Mbps (Mega bits per second) and the system level payload throughput around 6 Mbps. For average network user capacity the payload capacity is usually even much lower than 6 Mbps depending on the number users in the coverage area. In an ad hoc network, the capacity is a function of number of nodes and the level of mobility due to control traffic required to maintain topology information of the network. Furthermore, the capacity evaluation presented in the literature are biased by the used simulation tools. Therefore, the presented values in this paper and in the literature are more indicative than absolute.

3 Random numbers

Especially for the large-scale simulation models, design of a random number generator has an essential role, see [10] for more information. A definition of *randomness* in the context of computer-generated sequences can be stated so that the deterministic program that produces a random sequence should be different from and in all measurable respects statistically uncorrelated with the computer program that uses its output. Hence, two different random number generators ought to produce statistically the same results when utilized in a particular application program [1]. There exist a certain list of statistical tests for testing any correlations that are likely to be detected by an application program. As a reference to the topic, see Knuth [2] and Bratley [3]. In short, it can be stated that a reliable source of random *uniform deviates* is an essential building block for any sort of stochastic modeling or Monte Carlo computer work [1]. Uniform deviates are random numbers that lie within a specified range (typically from 0 to 1). However, there is other sorts of random numbers, *e.g.*, numbers drawn from a normal distribution with a specified mean and standard deviation. These are usually generated by performing appropriate operations on one or more uniform deviates.

4 Capacity Constraints

Ad hoc networks mostly have significantly lower capacity than in the wireless local area networks which use the same radio technology, channel reservation and data link protocols. In ad hoc networks, the capacity is severely limited due to deliver of *control information* and *misinterpretation* of network events by higher layer protocols. Moreover, the capacity of ad hoc networks with wireless local area links share the same inherent problems than wireless local area networks, *e.g.*, Aloha type medium access control (MAC) suffers from hidden node problem [2] in both network types. Lack of existing network infrastructure or centralized system management also provides that control and management of the network resources have to be done in a distributed way using available bandwidth and network topology.

Control information is mostly required to get mobility-induced topology/routing information and maintain it on the network nodes. For the topology information delivery, transmitting nodes are required themselves to compute routes to destination nodes and transmit topology information to neighboring nodes according to applied routing protocol. Routing protocols can be categorized, as mentioned earlier, to *reactive*, *proactive* and *hybrid* protocols. Reactive routing protocols define the most suitable route from source to destination when required. Proactive routing protocols update the topological information of the network continuously by time being. Therefore, each node in the ad hoc network is designed to serve as a router. In reactive protocols, the amount of delivered routing information increases as a function of nodes and frequency of events. Frequency of events is dependent on the number of nodes and the level of mobility. In proactive protocols, the amount of delivered routing information is dependent on the number of nodes and

[2] This problem refers to the situation where some nodes may not be observable to all nodes of the network, which may cause collisions and reduce considerably the amount of traffi c carried by the network.

the update time interval. However, update time interval should follow the level of mobility. In large networks, the amount of control information may consume a major part of or even all of the available bandwidth and get the network to congest.

IP (Internet Protocol) based ad hoc networks provide unreliable, connectionless, packet delivery in which packets can be lost or destroyed due to transmission errors, network hardware fails, or too heavy traffic load during the transmission. Networks may also dictate an optimal packet size or pose other constraints. Ad hoc networks, which route packets dynamically, can also deliver them out of order, deliver them with substantial delay, or deliver duplicates due to, *e.g.*, multiple routes or substantial delivery delay. Especially multipath routing may result in a significant waste of bandwidth due to fact that receiver generates multiple acknowledgments, which can cause the sender to invoke erroneously congestion control if connection oriented protocol is applied in the transport layer.

Misinterpretation of network events due to fact that some higher layer protocols such as TCP (Transmission Control Protocol) interprets erroneously, *e.g.*, retransmissions due to high bit error rate and network partition as congestion situations. Duplicate transmissions due to multiple routes and short timeout values during the disconnection and reconnection procedures also cause congestion interpretations in the TCP layer. Increased control information and misinterpretations dramatically reduce the level of utilization of the networks.

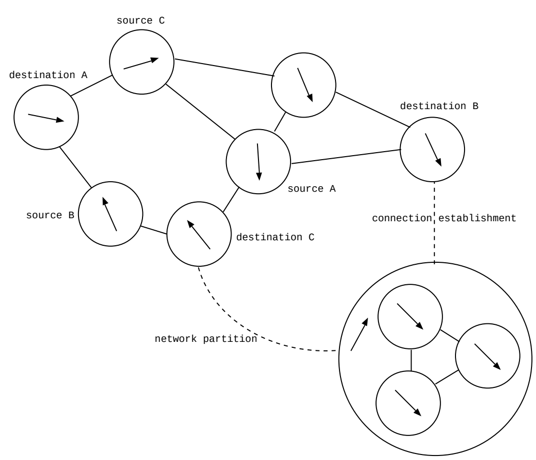

Figure 1: An ad hoc network.

For example, figure 1 presents a network partition and reunion. In Figure 1 three (3) nodes have lost connection to the network but are still capable to communicate with each other, *i.e.*, they are partitioned from the network until they rearrive to coverage area of the network and reconnect into the network. Route recomputation is required when the old route is no longer available. It is possible that the new route discover may take longer than retransmission timeout, RTO, at the sender. If the sender and the receiver lie in different partitions, all the packets get dropped by the network resulting in the sender to invoke erroneously congestion control. This might even get worse if partition lasts significant amount of time, several times longer than RTO, leading to the serial timeout condition, wherein multiple consecutive retransmissions of the same segment are transmitted to the receiver, while it is disconnected. The RTO timer is double after each unsuccessfull retransmission attempt until it reach its maximum value (64 s).

5 Discrete Event Simulation

One of the most important reason for the use of stochastic simulation is computational complexity of the research phenomenon. The computational complexity means that whether analytical solution for the problem is unknown or there does not exist any computationally efficient method for the exact problem solution.

Discrete event stochastic simulation is commonly used for the modelling of communication networks and communication protocols as it offers flexibility of performance modelling at any level of detail [4]. Network components like channel models, access technologies, traffic models, communication links, repeaters, routers, transceivers and various control structures of network elements are presented using computer program modules. Events of the network, like packet transmission, arrival, routing through the network, losses due to bit errors and buffer overflows, rejection, delays and link failures are mimicked in the simulation program execution.

Despite of wide range of application areas, discrete event stochastic simulation models share a number of common features and components. These includes, *e.g.*, system clock, event lists, statistical counters, initialization routines, timing routines, event routines, library routines and report routines to mention some of them. Here, we consider especially simulation clock and stochastic event's occurrence and duration times because of their definitive effects for convergence time. Convergence time refers to the minimum required simulation time of the model for the reliable results.

Simulation clock is a variable, which gives the current synchronized value of simulation time. Various events in discrete event stochastic simulation have random occurrence and stochastic duration times which obey either some known standard probability distribution or nonstandard, experimental, probability distribution. Monte Carlo based random sampling can be used to define duration times from these distributions.

Communication networks as large-scale systems are very complex. A simulation of them is, in an abstract level, parallel series of deterministic and stochastic events with predefined or random occurrence and duration times. Stochastic duration times are drawn from specified distributions using random number generator in which numbers are usually uniformly distributed on the interval [0,1] and do not exhibit any correlation with each other. The distributions can be some known standard distributions like normal, exponential, Poisson, Pareto and uniform distributions or nonstandard experimental distributions. A given random number indicates the duration time of the event. It is defined from the cumulative distribution of the duration time density distribution. In Figure 2 a given random number, *i.e.*, probability is 0.395 and it indicates to specific point in a cumulative distribution of an example event duration time. The respective duration time is got from the horizontal axe, 9.0 milliseconds.

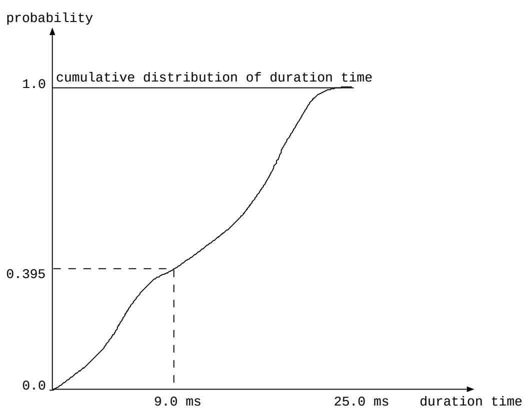

Figure 2: Duration time definition.

Deterministic duration time of the event refers to the fixed duration time. The occurrence time of an deterministic event is either triggered by other event(s) or transition to a specific state whereas stochastic event has probabilistic nature (like transfer error has) and it is stochastically defined by probability calculation. The random sampling method described above is called Monte-Carlo technique. The name Monte-Carlo method arises from the fact that the method uses random numbers like those coming out of roulette games.

The next event of the communication system is dependent on it's current state but independent on the way the state is reached. Therefore, communication networks with distributed elements can be modeled via *Markov chain theory*.

6 Convergence Time

In quantitative simulation studies special attention should be payed to accuracy of the final results of the simulated experiments. This is especially true for distributed ad hoc systems with highly parallel calculations. However, it is surprising to notice that in only a few reported simulation studies statistical analysis are carefully performed to control statistical errors on their final results. It has been noted already in 1990 that no any other field of science and engineering has not taken such a liberty with empirical data [5]. Marsan et al also points out in 1990 that simulation without careful statistical analysis of simulation output data can provide erroneous results [6]. This alarming trend has continued despite of the early warnings. The possible random nature of output data has been ignored in numerous publications and not least in the communication simulation field.

Random sampling of the series of stochastic distributions (standard or experimental) leads to total throughput or other selected reference value which depends on the number, types and parameters (variance, average etc.) of the distributions. Hence, for the reliable simulation of the effects of simulation parameters (velocity of nodes, routing protocols, timeout values) to the researched output, the simulation time for the developed model should exceed a convergence time of the model. Convergence time refers to the minimum simulation time of the model so that the throughput or other reference values achieved with fixed set of parameters do not oscillate significantly in sequential runs. According to the Central Limit Theorem (consult, *e.g.*, [7] for a general view or [8] for a more throughout mathematical explanation) a series of probability distributions obey normal distribution as a whole. The convergence time indicates to the minimum simulation time so that the expected value of this overall distribution is achieved.

In a simulation model development process, it is mandatory to define the convergence time of the model to get reliable results. The influence of some parameter, for example, to the throughput can not be judged with simulation times shorter than convergence time. This due to the fact that the reference value oscillates according to the random values (according to the variance of the series of distributions) of the event probabilities and duration times, which are evaluated in different sequential and parallel phases in the network. If the simulation time exceeds the convergence time, the effect of the simulation parameter under study can be seen on the output of the reference value. In a case of the parameter has influence(s) to the simulated system's behavior, the expected value and variance of the reference variable are changed when the value of the simulation parameter changes. Interested reader can find more details about the convergence times and communication simulations from [10].

7 Throughput optimization

7.1 Throughput of the Example Networks

In this article, an ad hoc network model was used for the reliable evaluation of various network parameter's effects to the throughput. The ad hoc network model was based on IEEE802.11b radio technology and AODV routing protocol. In careful simulation setups it was noticed that ad hoc network with 10 nodes and pedestrian mobility required even 2000 s simulation time before throughput converged (the throughput decreases towards 2000 s; in [10] has been shown the communication simulation cases where the throughput oscillates on the both sides of the convergence value before convergence time is reached). A simulation was considered to be converged when capacity fluctuated within 1% limits. Figure 3 presents throughput for data traffic of the ad hoc network with 10 nodes, AODV based routing and pedestrian mobility as a function of simulation time when simulation time spans from 50 seconds to 5500 seconds [9]. In the network all the 10 nodes were active. This was modelled so that 2 nodes (a source-destination pair) were transmitting data (file transfer) and other nodes were generating background traffic. The background traffic was generated by using random TCP generator and random waypoint algorithm to create node movement patterns. Each node is given coordinates to move in a three dimensional area. All the nodes consumed bandwidth also due to required control traffic for the network topology information update.

For the simulation of effects of, *e.g.*, extra transceivers the convergence time should be redefined due to increased number of degrees of freedom. The convergence time have to be redefined also if, *e.g.*, routing algorithm is changed or CCK (Complementary Code Keying) modulation/coding is changed to higher performance PBCC (Packet Binary Convolutional Coding) modulation/coding in the physical layer of ad hoc transceivers based on IEEE 802.11b standard or if connection oriented transport layer protocol is changed to connectionless protocol. In other words, the convergence time must be redefined for the changes, which clearly may effect to the capacity (throughput) of the network. However, if unsure the redefinition of the convergence time is always preferred and absolutely more acceptable than get erroneous results with too short simulation times.

Figure 4 presents throughput for data traffic of the same ad hoc network as a function of simulation time when it spans from 10 seconds to 50 seconds [9]. It can be noticed that, *e.g.*, for capacity simulations if simulation time of 20 seconds is used absolutely too optimistic throughput value (more than 3.4 Mbps) is achieved. The real capacity is only about 1000 kbps. From Figure 3 it can be noticed than even if the simulation time is much longer than 20s but still too short, *e.g.*, 100 s, the average throughput of 1.95 Mbit/s for the ad hoc network is achieved. However, the real capacity value is around 1000 kbps, which is about 51% from the erroneous result achieved with too short simulation time.

Figure 5 presents an average capacity of an ad hoc network as a function of number of nodes ranging from 3 to 50. For the three (3) nodes average throughput was around 3.8 Mbps and for the 10 nodes it was only 1000 kbps. Dramatic decrease in capacity was mainly due to increased number of packet collisions when the number of users grew. In larger networks, for instance with 50 nodes, the link failures become even more common and the network is rather congested. The average throughput for 50 nodes is only 116 kbps. This is typical behavior for a wireless systems with a random MAC (Media Access Control) based channel division/reservation algorithm. 116 kbps is very low for a local area ad hoc network with very limited coverage area and only pedestrian level mobility. It is very probable that with the higher level of mobility IEEE 802.11b WLAN standard based ad hoc networks will be fully congested due to increased packet error rate. Throughput value of 116 kbps may be enough for voice communication, poor level video transmission and other low data rate applications such as a short message delivery. It is definitely not enough for the fluent web browsing and email delivery, which are the most common applications of the WLAN IEEE 802.11b front-end networks. Therefore, ad hoc networks with higher data rate applications should be based on, *e.g.*, IEEE 802.11a technology with admission control, which offers 54 Mbps system level capacity.

7.2 Effects of Simulated Parameters

In this subsection is described the effects of simulated parameters, *Hello message interval*, *RTS/CTS (Request to Send/Clear to Send)* and *Active Route Timeout* procedures, to the capacity of the example ad hoc network described above.

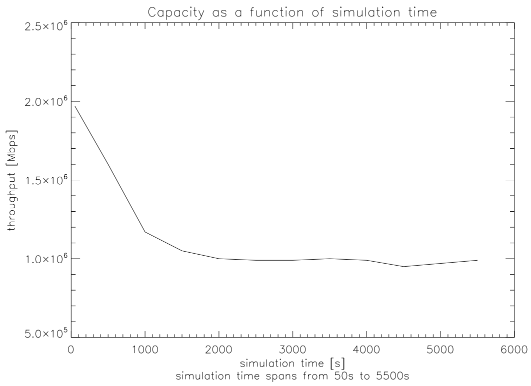

Figure 3: Throughput as a function of simulation time.

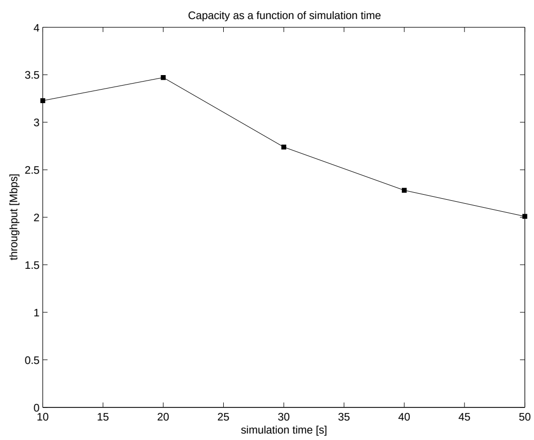

Figure 4: Throughput as a function of simulation time.

7.2.1 Hello Message Interval

In ad hoc networks neighboring nodes can communicate directly. Nodes keep track of their neighbors by listening for HELLO messages that each node broadcast at preset intervals. Commonly accepted default value for HELLO message interval is one second. In the simulations, different HELLO message intervals did not significantly effected to the capacity/throughput of the network, see Table 1.

7.2.2 RTS/CTS Procedure

As an optional feature, the IEEE 802.11b standard includes the *RTS/CTS* (Request to Send/Clear to Send) function as a part of the MAC layer functionality to control a node access to the medium. Enabling RTS/CTS on a particular node will refrain from sending a data frame until the node completes a RTS/CTS handshake (see Figure 6) with another node (in a normal WLAN infrastructure setting another node is an access point). A node initiates the process by sending RTS frame. The other node receives it and responds

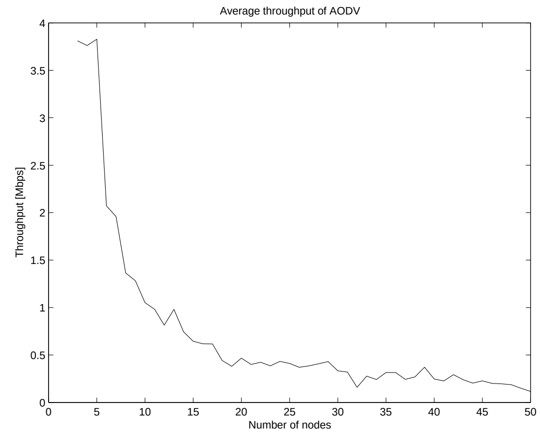

Figure 5: Throughput as a function of nodes.

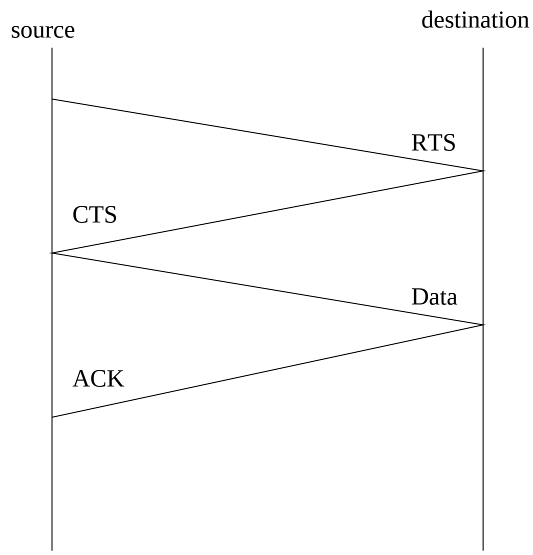

Figure 6: A four-way RTS/CTS handshake procedure ensures collision avoidance.

with CTS frame. The node must receive CTS frame before sending any data frame. CTS also contains a time value that alerts other nodes to hold off from accessing the medium (virtual carrier sensing) while the node initiating RTS transmits its data.

The RTS/CTS handshaking procedure provides control over the use of the shared medium. The primary reason for implementing RTS/CTS is to minimize collisions among hidden nodes which occurs when users are spread out throughout the facility and there are a relatively high number of retransmissions occurring. However, an increase in performance using the RTS/CTS procedure is the result of reducing traffic (fewer retransmissions) despite of the introduced overhead (RTS/CTS frames). Without any hidden nodes, the use of RTS/CTS will only increase overhead, which naturally reduces throughput.

For the RTS/CTS procedure a specific packet size threshold (0-18776 bits) can be set to initiate the RTS/CTS function. Therefore, the RTS/CTS procedure is initiated only for the packets which are larger than the defined threshold. Figure 7 presents the effects of optimization of the RTS/CTS procedure, *i.e*,, the effect of the packet size threshold value to the overall capacity. In Figure 7 is shown the throughput of networks for 3 to up to 10 nodes. The threshold value, which maximized the overall throughput was noticed to be 3000 bits. This means that the RTS/CTS function was initiated for the packets larger than the value of 3000. It can be noticed that the average throughput for the RTS/CTS optimized network is significantly higher for networks up to 9 nodes and remains almost the same level for networks up to 10 nodes compared to network without RTS/CTS procedure. This may due to that for the smaller networks (less users), the significance of hidden stations is higher, *i.e.*, the proportional share of retransmission due to hidden stations is higher for the smaller networks than larger networks.

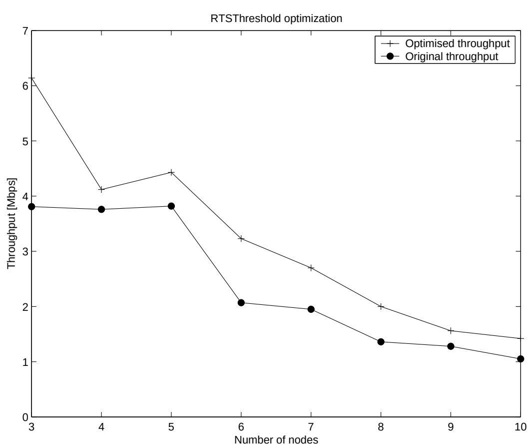

Figure 7: RTS/CTS threshold optimization.

7.2.3 Active Route Timeout

Active route timeout parameter in AODV routing protocol describes the lifetime of the active routes. The timeout optimization was carried out with constant traffic for 1 connection in the ad hoc network by changing timeout value from 1 to 49 seconds, see Figure 8. From it is seen that active route timeout does not have a significant effect to the average throughput. This was due to continuous data traffic which detain routes active until the mobility changed the network topology. Therefore, the data traffic was changed into alternate transmit and idle periods of three seconds. During the idle periods data traffic between the examined source-destination pair was halted and activated again during the transmit periods. When the last packet in the three (3) second data burst arrives, the timeout to that particular route entry is reset to the current time plus an active route timeout value. The active route timeout value was simulated for 10 nodes with values from one to eight seconds as illustrated in Figure 9 with active route timeout value of 3 seconds. The active route timeout value now affects to the throughput of the network and the optimized average throughput is achieved when active route timeout value approximately equals or is slightly over the traffic interval. Hence, the optimized timeout value was defined to be 3.5 seconds and an average throughput with it was 396 kbps. This may due to the fact that network defines the new routes when the transmission begins and they last during the transmission. The peak rate at 2.0 seconds may due to that Hello message interval is 1.0 second and 2.0 s + 1.0 s approximately equals optimized timeout value of about 3.0 seconds in which time the route update begins.

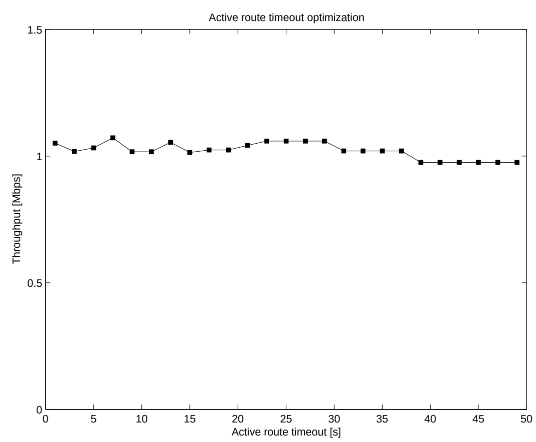

Figure 8: Throughput as a function of active route timeout.

After the timeout value exceeds the idle time (3 seconds) of the traffic the throughput saturates approximately to the level of 300 kbps. The defined route is not necessarily the optimal route anymore because the mobility changes the topology of the network. At that time the route discovery has to be reinitiated, which decreases capacity. Active route timeout optimization was performed with 4 and 5 seconds idle times for 10 nodes, in order to confirm the achieved results, see Figures 10 and 11. When idle period is 4 seconds there are two throughput peaks with active route timeout values of 1.5 seconds and 4 seconds. The throughput peak of 358 kbps with the value of four seconds is achieved also with the value which

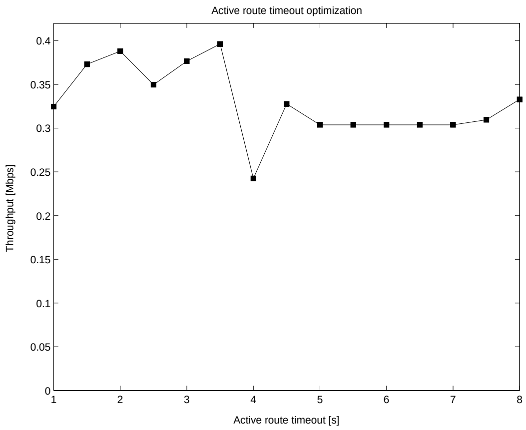

Figure 9: Throughput as a function of active route timeout with alternating idle-transmit periods of 3 seconds.

approximately equals the traffic interval like in the previous case. The biggest throughput value of 384 kbps is attained with an value of 1.5 seconds. The throughput saturates to the level of 260 kbps after the active route timeout exceeds the idle time (4 seconds) of the traffic. The throughput falls quickly after the optimized active route timeout value because capacity is required for updating the topology information which has changed due to mobility. For idle period of 5 seconds optimized active route timeout value is 5.0 seconds. Which equals the traffic interval. The average optimized throughput is 372 kbps. The throughput saturates to level of 200 kbps. Possible explanation of the high throughput with the active route timeout value of 1.5 seconds is explained by Figure 12. The time line illustrates the four seconds idle time of the traffic during which the nodes are moving. The hello message transmission begins during the idle period at 2.5 seconds (4.0 s - 1.5 s = 2.5 s). The network probably needs 1.5 seconds to update the neighbor information. The active route timeout value of 1.5 seconds optimizes the average throughput because the time {active route timeout + (n * hello interval) + time required for update neighbor information} approximately equals the idle period. There is a low throughput with the active route timeout value of 2.5 seconds, see Figure 12. The low throughput value is probably due to the insufficient neighbor information update period after the transmission of a hello message.

8 Observations

From results we can instantly observe that for the reliable calculations it is essential/mandatory to define the

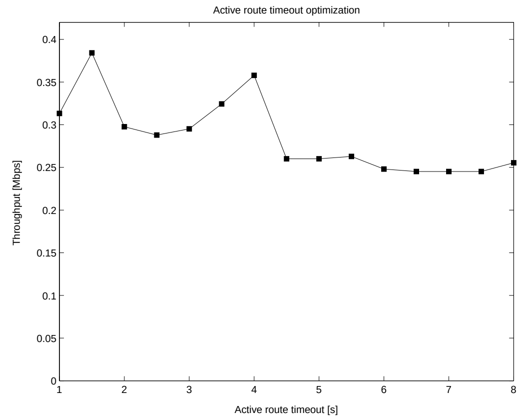

Figure 10: Throughput as a function of active route timeout with alternating idle-transmit periods of 4 seconds.

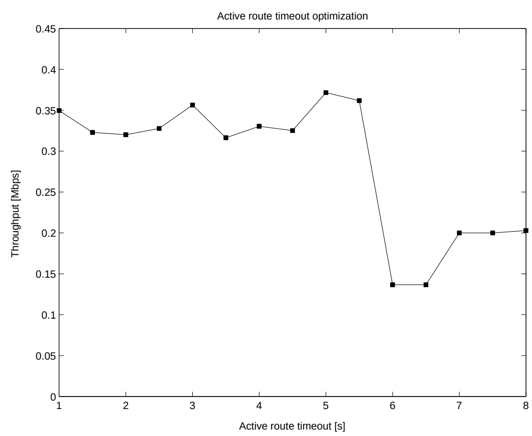

Figure 11: Throughput as a function of active route timeout with alternating idle-transmit periods of 5 seconds.

convergence time of the model and let the simulation time exceed it. The effect of a parameter to the value of reference variable, such as throughput or overall delay, can not be judged before implicit stochastic variance of the model is eliminated by a long enough simulation time. For the modeling of distributed systems, like communication networks, one should also notice effects of scalability to the convergence time because it is straightly dependent on, *e.g.*, the number of nodes in the model. Hence, increasing of the number of nodes or other feature(s), which increase stochastic distribution(s) to the model also change convergence time. In this kind of case, the convergence time must be redefined.

In complicated communication network simulations the convergence time grows as a function of nodes and frequency of events. It may extends to thou-

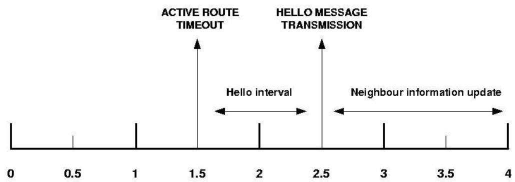

Figure 12: Active route timeout value of 1.5 seconds.

Table 1: Throughput with optimized parameters.

Parameter	Optimized value	Throughput
Hello interval	insignificant	1000 kbps
RTS/CTS threshold	3000 bits	2000 kbps
Active route timeout	insignificant	

sands of seconds for a network with 10 or more nodes and moderate mobility like has observed here and in numerous other simulation studies performed in Technical Research Centre of Finland, Cellular Systems group. This is probably due to increased number of degrees of freedom [3] and it may also be a sing or symptom of the sequential correlation on successive calls of the random number generator.

9 Conclusions

In this paper was described fundamentals of the stochastic communication systems simulation, which were based on Markov chain theory and Monte Carlo method. A convergence time of the simulation model was defined for reliable simulations. Without the convergence time definition, it is possible that results are incorrect.

For the modeling of distributed systems the effects of scalability to the convergence time is straightly dependent on the number of nodes and the degrees of freedom in the simulation model.

For communication networks like ad hoc networks with numerous nodes, moderate random mobility of nodes and continuous data transmission between the nodes, throughput either fluctuates, increases or decreases depending on the initial settings with simulation time until it reaches the convergence value. Hence, for example for reliable capacity estimates of networks convergence time must be carefully defined in order to avoid erroneous and unrealistic values.

[3] In ad hoc networks links can connect and reconnect and network can be partitioned in a random way, which effects to the convergence time are dramatic.

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