SSIM: A Multi-Resolution Fluid Traffic Simulator for MANETs

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ABSTRACT

Model abstraction techniques have been widely used to accelerate simulations in the context of homogeneous wired networks, whereas their applications to more complex network systems, such as wireless networks, are rare. This paper investigates how model abstraction techniques are applied to simulations of mobile ad hoc networks (MANETs). We introduced a multi-resolution simulation framework based on a fluid-oriented time-stepped (TS) traffic model. We conducted experiments using SSIM which is a session-level MANET simulator developed in the EE Department of Queen Mary University of London. Our results show that TS can speedup MANET simulation and improve scalability by reducing the number of events and the simulation running time.

Keywords: MANET, Simulation, Model Abstraction

1 INTRODUCTION

Simulations of MANET differ considerably from simulations of the wired networks in that they have to include modeling of the dynamic geographic environment and radio-based channel properties which both have profound effects on network performance. There are several discrete-event simulators which have gradually become the household names in the MANET community, such as ns-2, GloMoSim and OPNET etc (also see a review in [1]). Those simulators model the routing, radio transmission collision/interference, mobility, and other environmental effects in great detail. However, such high resolution simulation is computational expensive, particularly for modeling and simulation of large-scale networks. For example, it's estimated that a single simulation run of a MANET of 1000 nodes for a length of 1000 seconds needs about 65 hours to finish using ns-2 running on a Athlon 1.7GHz CPU workstation. In fact, fast simulation of MANETs of hundreds or thousands of nodes has been and will remain a challenging research topic, despite that the computational capability keeps becoming faster and cheaper.

In this paper, we proposed to use *model abstraction* techniques to improve the performance of MANET simulations. According to [2], model abstraction refers to: "*… reduce its (the model's) complexity while preserving its validity in an experimental frame*". Because applying model abstraction techniques often implies some degree of compromise in simulation granularity, the central issue is how to balance between the achieved speedup and simulation accuracy, which involves both technical and non-technical considerations. We introduced a multi-resolution simulation framework, which includes a variety of abstracted models, to help the simulation users to address the difficult issue of trading off simulation granularity for speedup. Those models are implemented in SSIM, a scalable session level MANET simulator, which is developed at the Networks Research Group in Queen Mary University of London (QMUL). This research is combined supported by the Electronic Engineering Department of QMUL and the EPSRC[1] project "Whole System Modelling of Large-Scale Communication Networks for What-If Evaluation", which is aiming to develop new methods for supporting large-scale network simulation and emulation capacity.

2 RELATED WORKS

In the literature, abstraction techniques have been widely applied to modeling and simulation of communication network systems. For example, an abstraction technique was proposed in [3] to simplify the modeling of wireless MAC (Medium Access Control) layer protocols. Heidemann et al [4] studied the effects of the details of wireless network simulation by investigating, in five scenarios, the trade-offs associated with adding detail to simulation models. In [5], the authors introduced the concept of transfer-level simulation as an alternative to packet-level simulation for large-scale wide-area networked applications and services, where the details of lower-level protocols are abstracted by analytical models. Focusing on the traffic model, the fluid simulation techniques [6, 7] approximate packet-level traffic by continuous traffic flows so that numerical approaches can be applied.

The philosophy of the abstraction approach is to try to ignore the trivial system properties and only put these most important ones into the model. Here the challenge is how to decide which part is important. Such a decision process is often subjective to the model developers, because the effectiveness and accuracy of model abstraction approach largely depends on where the model developers' intention lies, and how much they understand the system. Hence

[1] EPSRC is the UK Government's Engineering and Physical Science Research Council.

validation is crucial when using abstraction techniques. To address this issue, Zeigler et al [2] introduced a formalism to specify the modeling and simulation process, based on *System Theory* introduced by pioneers such as [8, 9]. They employ the concept, *levels of system knowledge*, and introduce a general framework under which each type of system problem solving can correspond to a particular level of detail in system knowledge. System theory provides a powerful theoretical tool for the validation of simulation abstraction approaches. In the context of MANET, the issue of validation was addressed in [10], where the authors experimentally checked some of the most widely used assumptions in the simulation research and concluded a set of guidelines in using simulation in MANET research.

3 SESSION-LEVEL SIMULATION

SSIM is a *session-level* simulator which focuses on simulating the sessions (connections) between co-operating applications rather than the protocol details at packet level. The concept of session-level simulation is motivated by the fact that data network traffic at packet level is extremely variable over a wide range of time scales. This variability is manifested by asymptotic self-similarity behaviour [11]. The complexity of the packet arrival process is proven to be very difficult to derive a packet level traffic characterization which is practical for performance modeling. Moreover, most traffic related network performance measures of interest invoke entities of higher level like the flow or the session such that it is more important to be able to describe and characterize traffic in these terms.

According to the OSI (Open System Interconnection) seven-layer network architecture, a traffic session is a loosely defined object representing a stream of packets having some criteria in common (destination nodes, port numbers, etc). A session-level communication manages dialogues between nodes and defines how the data conversations are established, controlled and terminated. In SSIM, the traffic is not simulated in a packet-by-packet fashion, but in flows. A traffic flow is defined by its starting time and the amount of data to be transferred, and it is not concerned with the syntax and semantics of the information which the traffic is bearing, nor is it concerned with the user-end application protocols that are used.

4 A MULTI-RESOLUTION FRAMEWORK

In high-speed networks, it has been found that the packets are communicated in a packet train pattern [12]. Once a packet train is triggered, the probability that another packet will follow is very large. In SSIM, the inherently bursty property of data network traffic is captured by the ON/OFF traffic model [13]. In this model, each single traffic source alternates between two states: an ON state, in which it produces data at a constant rate, and an OFF state in which it produces no data. It is assumed that consecutive ON and OFF sojourn times are independent, and have different distributions. The apparent advantage of the ON/OFF model is that it’s easy to implement. Moreover, the ON/OFF model can significantly reduce the effort for generating traffic with long-rang dependence characteristics [11].

In order to reduce the cost of the detailed packet-oriented simulation, SSIM employs an Event-Driven Fluid-Oriented (EDFO) traffic model to reduce the complexity of the traffic modeling. In an EDFO model, a close group of packets is modeled as a packet stream or packet train. Only two variables, which are traffic rate and fluid duration, are needed to describe the packet train. Events are only generated when the rate of a traffic flow changes. If the rates of flows change infrequently, large performance gains can be achieved using this technique. Extensive study has been done in the literature to analyze the performance of the EDFO model, e.g. [6, 7]. Since the model detail is reduced, the simulation results are not as accurate as those of the packet-level simulation. As with all abstraction techniques, the appropriateness of the method depends on the simulation requirements. With fluid models, the detailed information about individual packets is lost. Therefore, it’s not suitable for using an EDFO model to study subtle protocol dynamics on individual flows.

To further reduce the complexity of EDFO model, we proposed a sampling based Time-Stepped Fluid-Oriented (TSFO) traffic model to further speedup the simulation. In a time-stepped (TS) simulation, the simulation clock is discretized into equal-sized units of length h and the simulation advances from one time-step to the next. An important assumption for the time-stepped simulation is that all the events in one time-step are simulated as if they occur simultaneously.

In the literature, the TS traffic technique has been reported to be used on the simulation studies of fix-line networks and has achieved significant acceleration, e.g. [14]. The main difference of the TSFO traffic model proposed in this paper is that it is based on *sampling*, while the traditional TS model is usually based on *averaging*. In an averaging based TS simulation, the state-transitions (represented by events) captured within a time-step are cached; then when the current time-step ends, the simulation system is updated according to the averaged effects of all the cached events. In a sampling based TS simulation, the simulator takes only one of the state-transitions as sample and discards all the rest state-transitions in a time-step; then the system is updated according to the sampled state-transition. The sample point can be chosen arbitrarily, e.g. the two boundary points of the time-step. SSIM uses the left hand side boundary.

In general, the averaging based TS simulation requires more storage and computational capacity to perform the additional action of handling the cached state-transitions, while the sampling based TS simulation is less computational demanding, but it is more likely to cause discrepancy. Moreover, the sampling based approach is much easier for error analysis. The potentially large number of varieties of applications and contexts makes it very difficult to have a general error analysis approach for the averaging based method; while the sampling based approach needs few assumptions on the simulated object and doesn't need to consider the detailed meaning of each system state-change.

The purpose of applying the TS approach is to reduce the number of events, which is equal to the number of state-transitions generated by the traffic source. The length of the time-step *h* plays an important role in accelerating the simulation and controlling the discrepancy. Denote μ_{ON} and μ_{OFF} as the mean sojourn time in ON and OFF state of the traffic model. We have the following theorems regarding the effect of *h* on the simulation accuracy and speedup.

Theorem 1: *Assume that the EDFO process is second-order stationary. If the length of the time-step h satisfies:*

$$h = \mu_{\mathrm{ON}} \times \frac{\alpha}{\alpha + (1-\alpha)^2}$$

where

$$\alpha = \frac{\mu_{\mathrm{ON}}}{\mu_{\mathrm{ON}} + \mu_{\mathrm{OFF}}}$$

then, the averaged discrepancy between the EDFO process and the corresponding TSFO process vanishes when the simulation length l tends to infinity.

Theorem 2: *Assume that the EDFO process is second-order stationary and* $\mu_{\mathrm{ON}}, \mu_{\mathrm{OFF}} < \infty$. *While the simulation length approaches infinite, r, the ratio between the number of state-changes of the EDFO model and the TSFO satisfies:*

$$r = h \times \left(1/\mu_{\mathrm{ON}} + 1/\mu_{\mathrm{OFF}} \right)$$

Proof: Due to limited space, the proofs of the above two theorems will not be provided here, and they can be found in [15].

Theorem 1 and Theorem 2 indicate that increasing *h* has two sides of effects on the simulation. On one hand, μ_{ON} indicates the burstiness of the traffic source, and increasing μ_{ON} will decrease the overall throughput of a queueing network. Theorem 1 states that increasing *h* actually increases μ_{ON} linearly. Therefore, the discrepancy caused by applying the TS approach increases as *h* increases, though the discrepancy may not increase linearly with *h*. On the other hand, the simulation cost is often proportional to the number of events it handles throughout the simulation run. Theorem 2 states that increasing *h* linearly decreases the number of events generated by the input traffic model and consequently reduces the simulation cost.

In simulation practices, a clearly defined simulation objective is the key for successfully applying the model abstraction techniques. However, a simulation objective is not always so obvious to be able to translate into concrete specifications of simulation modeling directly. An important methodology to fill this gap is through a layered approach, i.e. to categorize the simulation objective into several levels of classes based on certain criterions, such as the granularity of the knowledge to obtain through simulation, or the amount of resource needed for the simulation and model activities. For example, Zeigler at el [2] proposed a multi-level conceptual frameworks to specify the level of knowledge one can achieve through simulation.

In this research, we propose a multi-level framework specifically based on the level of modeling resolution of traffic models. The proposed multi-resolution framework is illustrated in Figure 1.

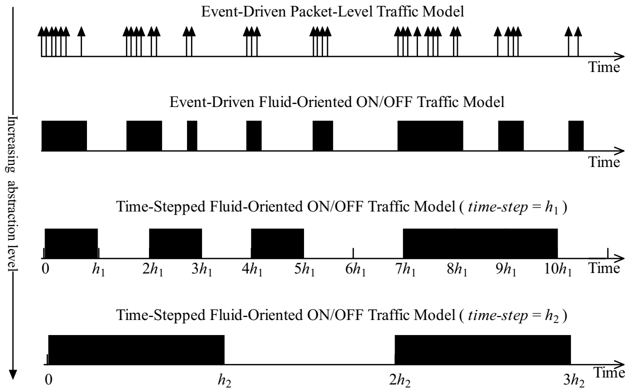

Figure 1: Multiple Simulation Abstraction Levels

On top of the figure represents the detailed event-driven packet-level simulation, such as ns-2, which can be considered to be accurate and served as a benchmark for comparing the accuracy of the abstracted simulations. The first level of abstraction models the network traffic as EDFO ON/OFF flows. Since the rate of the traffic fluid changes at a rate that is typically much slower than the packet sending rate, the simulator is expected to handle fewer events, thus achieving a simulation speedup. At the next level of abstraction, the network traffic is modeled as a TSFO ON/OFF process, which represents a coarser level of abstraction. At this level, some of the overall network traffic statistics, such as the traffic delivery ratio and the overall throughput can still be accurately simulated, but the detailed real-time traffic rate change is abstracted out of the model. At the highest level of abstraction, the length of the time-step is increased. As a result, the number of events generated by the input traffic model is further reduced; and consequently the simulation results become less accurate. Error analysis and validation is crucial at this stage. The simulation at this level is particularly useful for generating background traffic in a large-scale network, which often needs to superpose a large number of ON/OFF traffic sources.

5 IMPLEMENTATION OF SSIM

SSIM is a collection of objects of the mobility, traffic, radio, propagation models, etc, together with two input profile generators. SSIM organizes the models according to the network protocol layer to which each model belongs. This layered structure makes it convenient to switch among different models with different implementations and levels of granularity. The interfaces between the objects of different network layers are compatible with ns-2 because there is a big community of ns-2 users and contributors. Keeping compatible with ns-2 is a great advantage which allows rapid integration of the newly emerging models developed for ns-2, especially those of which have already been validated. This can significantly reduce the amount of effort for new model development. Table 1 compares the models developed in SSIM and ns-2 respectively. Most of the models listed in Table 1 are similar to the implementations in ns-2, and we will only briefly describe the MAC and routing models here because their implementations are different from the corresponding ns-2 implementations.

One difficulty of using the fluid-oriented simulation is that the simulator no longer tracks individual packet while some of the network protocols, e.g. MAC and routing protocols operate in a distributed way by exchanging administration messages. These messages are discrete and hardly come in a trunk fashion as the data traffic. Therefore, those behaviours of the protocols can no longer be simulated in a fluid-oriented simulation. This problem can be tackled by the *centralized computing technique* [16], which computes the direct effects of message exchanges instead of keeping track of every individual packet. In the context of session-level simulation, the focus is on understanding the behaviours of the connection level transmissions. Therefore the details of lower layer protocols such as the physical, MAC or routing protocols can be simplified as long as the overall transmission behaviours of the models are preserved. This allows us to abstract the detailed message exchanging in MAC and routing protocols by their direct effects.

In SSIM, bandwidth contention among transmission sessions is centrally managed by sharing the available bandwidth evenly among the contending transmissions. Thus the allocated channel bandwidth is the MAC capacity divided by the number of active transmissions that are contending the bandwidth. Unlike the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) MAC mechanism implemented in the ns-2's MONARCH extension, the MAC mechanism in SSIM is essentially an ideal asynchronous Time Division Multiple Access (TDMA) model, where the channel is divided into time slots and each transmission session is allocated with a unique share of time slots. Because of the simplicity of the TDMA MAC mechanism for both implementation and analysis, it also has been widely used in the Quality of Service (QoS) studies of MANETs [3].

Table 1: Comparison of models of SSIM and ns-2

Layer	**SSIM**	**ns-2**
Session	Fluid CBR, EDFO	Discrete CBR, EDFO
Network	Centralized Shortest-Path Routing Model	Distributed Routing Models: e.g. DSR, AODV, DSDV
Data Link	Centralized TDMA; Fluid FIFO Drop-Tail queue	Distributed Models: e.g. CSMA/CA with RTS/CTS; Drop-Tail queue
Physical	Free Space Propagation Model; Random Waypoint Mobility Model	Lucent WaveLAN; Random Waypoint Mobility Model

The routing information in SSIM is centrally computed directly based on the connectivity state. SSIM maintains the network topology as a matrix $\{c_{ij}\}$, where c_{ij} represents the connectivity between the node *i* and node *j*. $c_{ij} = 1$ suggests that the node *i* and node *j* are within the communication range of each node; otherwise, it is zero. The routing module employs the ns-2's GOD (General Operations Director) module to provide the shortest-path routing. When a mobility event, such as the change of the moving direction or speed of a node etc., happens, GOD updates the topology matrix by computing the all-pair shortest path using the Floyd-Warshall algorithm. Each traffic session in SSIM's stores the current route of the transmission. After GOD updates the topology, the stored route of each traffic session is compared to the new topology to see whether it is necessary to change the current route.

6 PERFORMANCE OF ACCELERATION

An intuitive method of measuring the simulation cost is by recording the wall-clock simulation time. The longer it takes to finish a simulation run, the more computational resources the simulation needs. However, the running time of a simulation often depends on the underline hardware and software configurations. Hence, the wall-clock simulation time alone cannot be an effective reference for the simulation's computational demand unless these factors are taken into consideration.

On the other hand, in a discrete-event simulation, we can consider the computational effort involved in handling each event as the basic unit of simulation workload. Thus the number of events (NoE) is an ideal choice for evaluating the cost of discrete-event simulations which are independent of the simulation running environments.

In order to illustrate the acceleration performance of SSIM, we carried out simulations using SSIM and ns-2 respectively, and compared the NoE and the wall-clock time of the two simulators. The fixed parameters of the experiments are listed in Table 2.

Table 2: List of fixed simulation parameters

Fixed Parameters	**Value**
Terrain size (meter^2)	800^2
Radio interference range (meter)	250
MAC capacity (Mbps)	2
Fluid Interface queue size (Kb)	500
Mobility Model	Random Waypoint
Pause time (seconds)	200
Average nodal speed (m/s)	10
Traffic Model	ON/OFF
Type of traffic during ON state	Constant Bit Rate
μ_{ON} seconds	3
μ_{OFF} seconds	3
Number of nodes	50
Simulation length (seconds)	500

Figure 2 and Figure 3 show the speedup magnitude of SSIM comparing to ns-2 in terms of wall-clock simulation time and NoE respectively. It can be seen that in both cases, the speedup magnitude increases as the scale of the network, i.e. the number of nodes, increases. This indicates that SSIM achieves better scalability than the ns-2 because the model abstraction techniques used in SSIM. However, the rate of the speedup magnitude decays rapidly as the number of nodes increases. This is due to the fact that SSIM only reduces the simulation cost of traffic related operations. While the network scale increases, the proportion of the traffic related operations to overall simulation cost becomes less and less.

Figure 4 and Figure 5 show the speedup magnitude of using the TSFO traffic sources comparing to the EDFO traffic sources. Two types of distributions, the exponential and the Pareto distributions, were used to denote the distribution of the sojourn time during the ON or OFF state. Note that R denotes the speedup magnitude of the wall-clock simulation time and the plot in Figure 4 is the reciprocal of R. In both figures, we can see that the speedup magnitude increases monotonically with the length of the time-step. However, the similar pattern of decaying speedup rate can be observed as in Figure 2 and Figure 3 as well.

7 CONCLUSION

In this paper, we broaden the application of model abstraction techniques to MANET simulations and provide a procedure to analyze the simulation error through both analytical and experimental methods. We proposed a multi-resolution traffic simulation framework for the simulation studies of MANETs with different levels of requirements in simulation granularity. We introduced a session-level simulator, SSIM, which integrates a variety of simulation acceleration techniques. Comparing to ns-2, our experiments show that SSIM can achieve speedup magnitude about 18 times in terms of simulation running time and 11 times in terms of NoE.

There are still several important issues open for future investigation, e.g. the effect of simulation length on time-stepped simulation and an analytical guidance on choosing the length of the time-step. Furthermore, the application range of model abstraction is not necessarily confined to the networking community.

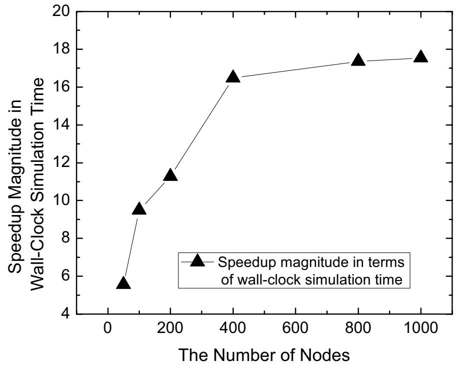

Figure 2: Wall-clock simulation time reduction magnitude: SSIM vs. ns-2

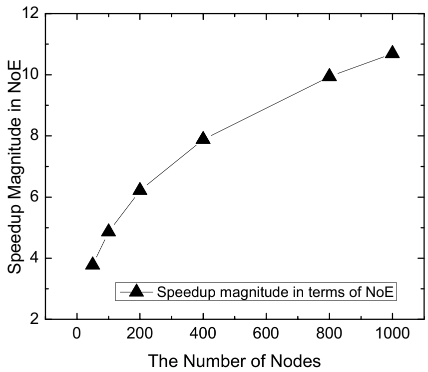

Figure 3: NoE reduction magnitude: SSIM vs. ns-2

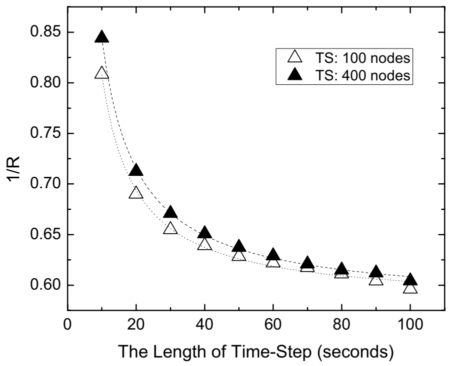

Figure 4: TSFO traffic; $1/R$ vs. h

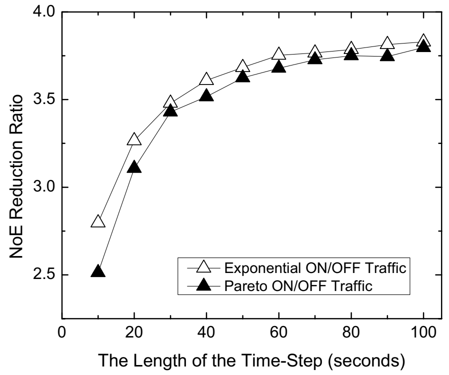

Figure 5: TSFO traffic; NoE reduction rate vs. h

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