STOCHASTIC MODELING FOR HYBRID NETWORK SIMULATIONS

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Network-Centric Warfare (NCW) is an objective of the Department of Defense (DoD). By networking large numbers of soldiers, sensors, vehicles, and other equipment, NCW will create an explosion of data in DoD networks. By the same token, Mobile ad hoc networks (MANETs) represent a critical technology for the Armys NCW vision. MANETs are currently an unproven technology that have not been modeled at scales relevant to realistic tactical operations. While research toward understanding the emergent properties of MANETs is progressing, we are far from realizing successful deployment of MANETs even at smaller scales (hundreds of nodes), and this leaves many open questions in realistic settings.

Satisfactory evaluation of the technologies supporting these scenarios will not be realized without the development of accurate computer simulation models. These models will involve thousands, perhaps hundreds of thousands of nodes. Such models create prohibitively large state spaces to be accommodated under the current state of the art. Parallelization of network simulation computation offers little benefit due to the end-to-end nature of applications. In addition to the difficulties created by excessively large state spaces, measurements from communication networks indicate that traffic patterns can be bursty and complex [1]. This leads to extremely long simulation time intervals. Standard statistical techniques used in estimating these intervals are not always applicable.

To reduce the simulation experiment to a tractable size, researchers seek to incorporate analytical tools into the simulation models. Existing models treat background traffic as deterministic fluids, or as solutions of deterministic differential equations. With these approaches, mixing simulated packet events into the analytically expressed background traffic turns out to be a challenging task. Issues with existing solutions include: i) they miss the incremental impact of newly generated packets into the performance of the overall system, ii) they do not adequately capture stochastic aspects and salient statistical properties of the background traffic, and iii) most importantly, they have degraded accuracy which tends to deteriorate at high traffic loads [2].

To accurately integrate the analytically represented background traffic with the simulated discrete packets, we propose to treat the background traffic as a stochastic process, and introduce a statistically sound method to incorporate the impact of discrete event packets in the overall system performance. Figure 1 shows our method for mixing analytically modeled stochastic background traffic with explicitly generated discrete event packets. Individual packet arrival events are indicated along the bottom axis of the figure. These packets carry with them a given workload which is a function of their packet size and the link bandwidth serving the queue in question. If a packet is allowed to enter the queue, then the workload in queue jumps by the amount of work carried by the packet. In between packet arrivals, the workload evolves according to a stochastic process whose statistics depend on the associated arrival process. Whether a packet is admitted due to congestion is dependent on the realization of the stochastic process describing the workload.

Under general assumptions, one can show that the background traffic can be modeled as a Brownian Motion, when link utilization is high. Actually, it is under high link utilization conditions that running reliable simulation models becomes particularly challenging. In general, mission critical applications display high sensitivity to the performance parameters under heavy traffic loads. When the background traffic is modeled as a Brownian Motion, its Probability Density Function (PDF) can be obtained analytically. This forms a robust framework into which individual simulated packets can be incorporated easily and accurately, while drastically reducing the computational burden of large scale simulations.

We have implemented an initial version of our approach using GTNetS [3]. Figures show a side-by-side comparison of the results obtained using our proposed method versus current state-of-the-art [4]. The baseline consists of a packet-by-packet simulation, which would be infeasible to perform in a large scale

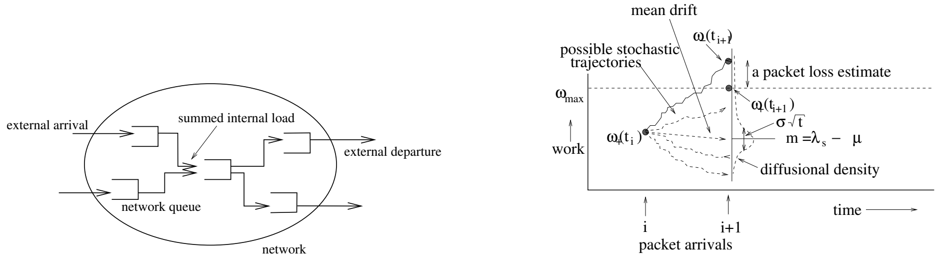

Fig. 1. Methods for development of a hybrid stochastic/event network simulation capability.

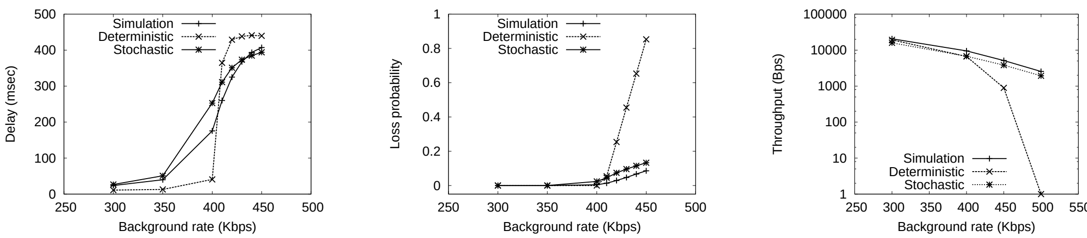

Fig. 2. Representative result for UDP and TCP packet flows.

network. The baseline plot is denoted by Simulation in the figures. Plots from existing hybrid simulation methods are denoted by Deterministic, while plots from our proposed hybrid simulation methods are denoted by Stochastic. The first two plots depict the delay and the loss probability incurred by UDP packets as a function of the intensity of the background traffic. Our method tracks closely the Baseline case, while the state of the art exhibits significant deviations at high utilization. The last plot depicts the throughput estimates of TCP applications as a function of the background traffic intensity. Again, our stochastic method closely tracks the Baseline simulation case, while the state-of-the-art deterministic method exhibits significant deviations at high utilization.

Our proposed stochastic method to accelerate large scale network simulations demonstrates clear advantages over current state-of-the-art. These include: i) natural integration of individual packets into the analytical model, ii) more accurate performance results, especially at high loads, and iii) important statistical properties of the background traffic can be accurately incorporated into the models, such as variance, burstiness, self-similarity, and heavy-tailed distributions.

Our initial results indicate that our stochastic approach is very promising for reducing the simulation workload while preserving its accuracy. We are planning to extend our results to a network of queues. To this goal, heavy traffic approximation methods will allow us to derive a set of Partial Differential Equations for the density functions. These equations can be solved numerically to obtain the needed density functions at each queue in the network. We can further reduce the computational load by focusing on each queue in isolation. Then, we can account for the impact of the interconnections among the queues using network calculus approximations reported in [5]. Finally, we plan to make use of Kalman filtering techniques [6] to incorporate changes in background traffic statistics in order to further improve accuracy of results.

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