Progressing Towards Realistic Mobility Models in VANET Simulations

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***Abstract*—Much progress can be observed in the domain of Vehicular Ad Hoc Network (VANET) research looking back at the last decade. It can be seen that studies of vehicular communication protocols in the context of VANETs are typically based on simulation models. This approach has two major prerequisites: First, detailed network simulation of all layers of communication protocols is necessary as provided by a wide variety of tools by the networking community. Secondly, realistic simulation of vehicles' mobility, i.e. an exact modeling of road traffic, is needed to estimate positions and movements of involved components. The contributions of this paper are twofold: First, a survey of the evolution of mobility modeling in VANET simulations is provided, outlining the simulation strategies typically used. Secondly, this paper investigates how recent advances in bidirectional coupling of road traffic microsimulation and network simulation lead to more realistic results at comparably low computational cost. In conclusion, this paper advocates to employ such techniques that are openly available for further studies of new communication protocols and mechanisms in the domain of VANET research.**

I. Introduction

Research activities in the Vehicular Ad Hoc Network (VANET) domain are becoming increasingly important for advances in multiple application fields of car-to-car communication including all car-to-X scenarios [1]. Results are used for example in approaches to reduce traffic congestion and provide general information services. In addition, safety-critical applications such as enhanced lane and distance control and emergency break warnings are profiting from improved VANET technology.

Most of the specific application scenarios require a wide variety of communication protocols. These are ranging from single hop broadcast for localized information exchange among neighboring cars up to multihop routing protocols for centralized traffic control services and even ubiquitous Internet access [2]. The employed wireless communication technology is focusing on IEEE 802.11 based networks but extends to include 2.5G and 3G telecommunication networks.

Studying recent publications, single hop wireless communication protocols are focusing on safety applications [3], whereas multihop protocols dominate in the areas of traffic congestion avoidance and dedicated information systems [4]. In all these domains, a huge number of protocols have been proposed in the last decade and this trend is continuing. As an alternative to classic Mobile Ad Hoc Network (MANET) routing protocols, recent approaches exploit network-centric data (pre-)processing and directed broadcast communication as used for example in completely self-organizing traffic information systems based on local broadcast communication [5].

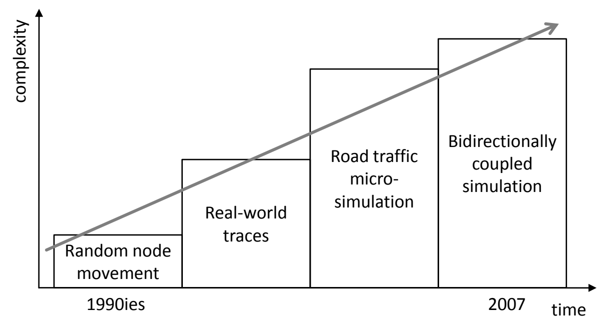


Fig. 1. Historical evolution of mobility modeling strategies and techniques in VANET research

Performance evaluation of developed protocols is typically accomplished by means of simulation techniques because realistic field tests are still infeasible or are limited to a few hundred cars as used in several recent research projects in Europe, the United States and Asia. The simulation of the VANET protocols, such as wireless communication, multihop routing, and application-aided broadcast, is typically performed in network simulation environments such as ns-2[1] or OMNeT++[2]. The main advantage is the availability of precise and well-tested models of communication protocols. Nevertheless, these simulators are not sufficiently equipped for adequately simulating the mobility of moving cars. Transportation and traffic science classifies traffic models into macroscopic, mesoscopic, and microscopic models, according to the granularity with which traffic flows are examined. Simulations of VANET scenarios are concerned with the accurate modeling of single radio wave transmissions between nodes and, therefore, require exact positions of simulated nodes. Only microscopic simulations, which model the behavior of single vehicles and interactions between them, can be considered as an adequate mobility model for simulated VANET nodes.

The main focus of this survey article is to outline the evolution of the VANET simulation strategies with emphasis on mobility characteristics. Section II is devoted to a historical

[1] http://www.isi.edu/nsnam/ns/
[2] http://www.omnetpp.org/

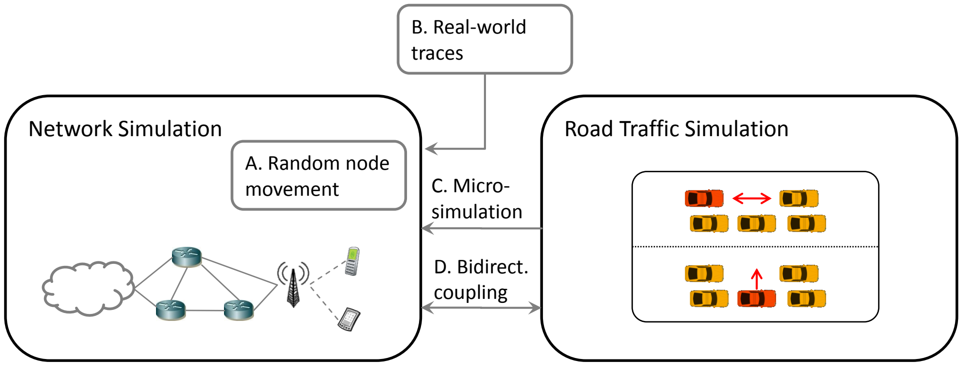


Fig. 2. Mobility modeling techniques for simulation of VANET protocols and applications

TABLE I
OVERVIEW OF MOBILITY MODELS, THEIR LEVEL OF SUPPORT IN SIMULATION FRAMEWORKS, AND THEIR PARTICULAR BENEFITS AND DRAWBACKS

Mobility Model Class	**Integrated Framework Support**	**Benefits**	**Drawbacks**
Random Movement	Virtually All	⊕ Straightforward, intuitive ⊕ Readily available	⊖ Imprecise ⊖ Potentially unstable
Real-World Traces	GloMoSim, QualNet, OPNET, ns-2, Shawn, JiST/SWANS, OMNeT++/INET Framework	⊕ Most realistic node movement ⊕ Re-usable traces	⊖ Costly and time-consuming ⊖ No free parameterization
Artificial Mobility Traces	GloMoSim, QualNet, OPNET, ns-2, Shawn, JiST/SWANS, OMNeT++/INET Framework	⊕ Realistic node movement ⊕ Free parameterization ⊕ Re-usable traces	⊖ No feedback on driver behavior
Bidirectionally Coupled Simulators	Ongoing efforts for: ns-2, Shawn, JiST/SWANS, OMNeT++/INET Framework	⊕ Realistic node movement ⊕ Free parameterization ⊕ Feedback on driver behavior	⊖ No re-usable traces

overview of different mobility modeling approaches used for VANET simulation. Based on the results drawn from this survey, we explicitly advocate the use of more sophisticated mobility models in all further studies of VANET protocols.

The survey part also includes a description of the most recent approaches for bidirectionally coupled road traffic microsimulation and network simulation based on a special coupling interface. The advantages of such coupling strategies are outlined in Section III. Based on sample simulation results, we clearly show the need for more realistic mobility modeling and a tight coupling of road traffic microsimulation and network simulation.

II. Mobility Modeling

The historical evolution of mobility models used in simulations of VANET protocols and application is illustrated in Figure 1. Early approaches relied on relatively simple models using random node movement. Because such mobility models do not realistically reflect car movements on roads, more complex solutions have been developed based on real-world and artificial traces of car movements up to recent advances based on tightly coupled road traffic microsimulation and network simulation. It is obvious that the inherent complexity of such mobility models is strongly increasing.

Figure 2 displays an architectural view on mobility modeling in VANET simulation. While random node movement is usually an integrated component of state-of-the-art network simulation tools, traces can only be obtained by external processes. Finally, bidirectionally coupled simulation relies on intensive intercommunication of the different simulation tools using appropriate interfaces.

In the following, we explain the different mobility models in more detail, roughly following the historical time line. The benefits and drawbacks of the mobility model classes are summarized in Table I.

A. *Random Node Movement*

In the early days of ad hoc network research, for the movement of nodes in an unconstrained, completely random manner, termed the *Random Waypoint* mobility model [6] served as the mobility model of choice. In 1997, the European Telecommunications Standards Institute (ETSI) then recommended that, for the evaluation of radio transmission technologies of the Universal Mobile Telecommunications System (UMTS), mobile nodes should move along a grid of possible ways – the *Manhattan Grid* [7]. However, this recommendation only covered the case of pedestrian mobility modeling; the recommended model of vehicles' mobility still used plain random node movement.

Although Random Waypoint based mobility models were shown to provide vastly different results from more sophisticated vehicular mobility models, sometimes not even reaching a steady state [8], derivatives of them have been in use ever since. This can in part be attributed to their ease-of-use, where straightforward adaptations, e.g. the consideration of inertia or the constraining of vehicles to predefined roads, provide realistic-looking movement patterns and are already able to produce significantly different results than a plain Random Waypoint model [9].

B. Real-world Mobility Traces

Compared to the use of random waypoint mobility models, the modeling of node mobility based on sets of pre-recorded real-world mobility traces was a major step towards realistic vehicle simulation. Such traces were obtained e.g. from a 2003 observation of city busses [10] or the logging of Global Positioning System (GPS) information. In the case of most approaches, real-world vehicles were tracked using on-board or subsidiary devices and vehicle positions recorded at regular intervals. These mobility traces were then post-processed and stored. During network simulations, node mobility was controlled by reading in these trace files and replaying them, synchronizing simulated nodes' positions with their corresponding vehicles' locations after each timestep. While such a mobility model will arguably result in the most realistic vehicle movement in network simulations, its use is limited by this approaches' inherent limitation to a small set of mobility parameters. Changing only one parameter, e.g. the density of vehicles, and keeping all other parameters unchanged is simply infeasible in reasonably large scenarios.

C. Artificial Mobility Traces

The restriction of trace data on what could be recorded from real-world vehicle movements can be – and was – easily overcome by generating such movement traces artificially. Here, the realism of node movement was only constrained by the complexity of the mobility simulator used. Approaches range in complexity from simple, collision-free node movement, as was done in a 2004 study [11], to the use of common mobility models from the field of transportation and traffic science [12], or the use of a fully-featured mobility simulator[3], the Multi-agent Microscopic Traffic Simulator (MMTS), employed for simulation experiments performed in 2006 [13]. To illustrate the complexity of the MMTS, here mobility is modeled by first deciding e.g. where each user is likely to live and when the user would get up in the morning, then picking a likely destination and mode of transportation according to the perceived congestion of roads. Only then are actual movements of vehicles, private or public means of transport, simulated.

This way, artificial mobility models have the advantage of providing simulations with very realistic mobility traces while at the same time allowing for the mobility parameters to be freely adjusted in order to examine their influence on a simulation's outcome. Still, many questions in the context of VANET simulations can not yet be answered by this simulation approach alone. Not only is node mobility influencing network connectivity, and hence network traffic, but in many real-world VANET scenarios network traffic is also influencing node mobility.

D. Bidirectionally Coupled Simulators

In cases where e.g. accident information, hazard warnings, or road congestion information, which can be assumed to influence drivers' behavior, are transmitted over the VANET, the loop between road traffic simulation and network traffic simulation needs to be closed. This requires intensive cooperation among the different simulation tools. Such bidirectionally coupled simulators [14], [15] have recently been developed and could be shown to not only provide more detailed insights into effects on (and of) network traffic, but at the same time to have only negligible impact on the run-time of simulations. Still, an inherent property of this approach is that the results of the road traffic simulation cannot be re-used in the form of trace files, as in bidirectionally coupled simulations node mobility is always computed on-the-fly.

In these simulations, two inter-dependent processes are running concurrently, namely the network simulator and the road traffic simulator. Both processes share data like position and speed of simulated vehicles, while other data like radio state and planned route is local to the network simulator or the road traffic simulator, respectively. Movement information updates about simulated vehicles are exchanged in regular intervals. So, bidirectionally coupled simulation of VANETs generally consists of two alternating phases:

1) While the network simulation is running, it sends parameter changes to the road traffic simulation, altering driver behavior or road attributes, and influencing vehicles' routing decisions. Simulation time advances only in the network simulator.
2) At regular intervals, the road traffic simulation performs traffic computations based on these new parameters and sends vehicle movement updates to the network simulation. Simulation time advances only in the road traffic simulator.

Ongoing efforts to create a multi-purpose communication interface between road traffic and network traffic simulators, coupling e.g. the SUMO road traffic simulator[4] with popular network simulation frameworks like OMNeT++ or ns-2, hint at the possibilities that such an approach can offer. Researchers from the network simulation community can now directly build on the work of researchers from the transportation and traffic science community – and vice versa.

III. Impact of Mobility Models

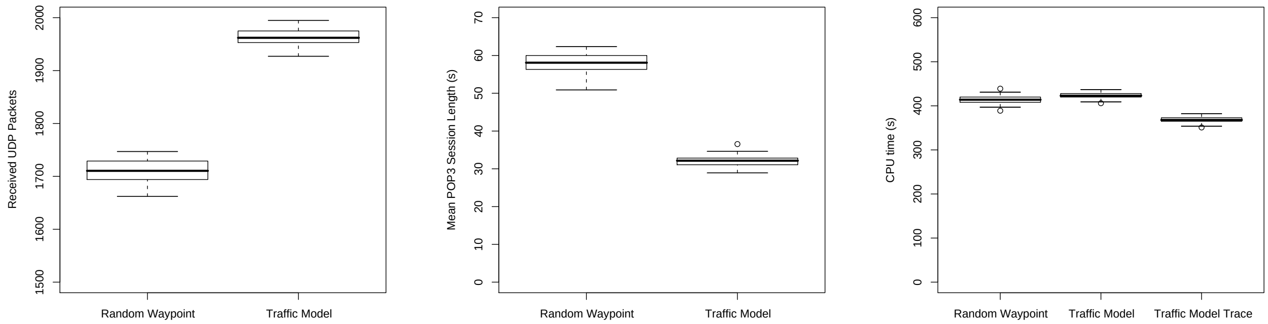
The impact of accurate mobility modeling on network performance can be judged by comparing results from an identical simulation scenario being fueled by different mobility models. In the following, we present selected simulations and compare results obtained using a random waypoint mobility model, mobility traces, and bidirectionally coupled road traffic and network simulators, respectively.

A. Mobility Traces

In [12], we simulated cars traveling on a circular road, their movement being at first modeled using a plain random waypoint mobility model. Nodes were placed at random points of a rectangular area corresponding to the road, picking random destinations, then traveling there at a constant speed. As soon as a node arrived at its destination, it picked a new point on the playfield and started moving again.

[3] http://lst.inf.ethz.ch/ad-hoc/car-traces/

[4] http://sumo.sourceforge.net/



(a) UDP packet transmission success rate

(b) mean POP3 session length

(c) simulation run time

Fig. 3. Impact of mobility model on UDP packet transmission success rate, mean POP3 session length, and simulation run time. Simulations used a random waypoint mobility model or the IDM/MOBIL models, with traces being generated both on-line or off-line

We then simulated the same scenario using the well-established IDM/MOBIL vehicular mobility models[5] to compute realistic lateral movement and lane-change decisions. The scenario was set up to model a VANET of vehicles, established with the help of the Dynamic MANET On Demand (DYMO) routing protocol. In particular, we compared the influence of the chosen mobility model in the context of two communication scenarios: In the first scenario, simulated cars polled traffic information from an Internet host using short UDP packets. In the second scenario, we simulated vehicles checking a POP3 mailbox using TCP connections.

Figure 3 shows the results of this evaluation. As can be seen, in both communication scenarios a noticeable impact of the chosen mobility model became evident. Regarding simulation run-time, an increase of only approx. 2% was recorded when movement traces were generated on the fly. Network simulation run-times could even be decreased compared to the use of a Random Waypoint model if pre-recorded vehicular movement traces were used.

B. Bidirectionally Coupled Simulation

To further examine the impact of unidirectional vs. bidirectional simulator coupling, we present data from a second set of experiments, detailed in [15]. For these experiments, the Veins framework was used. Veins is publicly available[6] and provides bidirectional coupling of network and road traffic simulation based on the OMNeT++ and SUMO frameworks, respectively.

For the evaluation of the impact of the simulator coupling, we simulated a network of roads, one lane per driving direction, laid out in an evenly-spaced grid pattern. One by one, up to 1000 vehicles started at a common source, heading to a common destination. In a reference scenario, all traffic was allowed to flow unhindered, so all vehicles traveled along the shortest path between source and destination. In a second scenario, we then introduced an artificial traffic incident by simulating a car breaking down on a single-lane road, blocking it for several minutes. Vehicles now participated in a VANET, exchanging congestion warnings between one another. Based

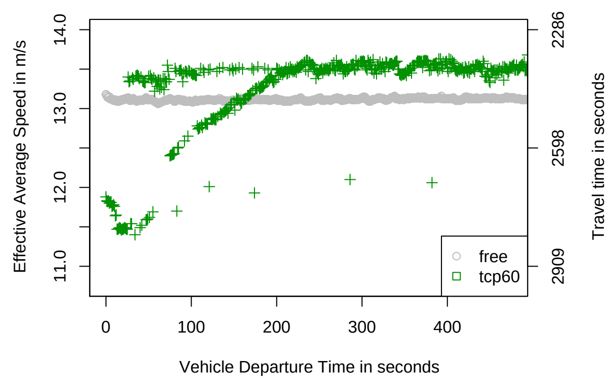


Fig. 4. Impact of VANET communications on vehicular mobility. Plotted is the average speed of individual vehicles, ordered by time of departure. One scenario with free flowing traffic and no communication, one scenario with a simulated incident of 240 seconds and VANET communications.

on these congestion warnings, vehicles then dynamically re-calculated the best path to their destination, taking alternative routes to avoid congested roads. For each vehicle, a complete Internet protocol stack on top of IEEE 802.11b network cards was modeled in the network simulation. We were thus able to illustrate the impact that congestion warnings exchanged between vehicles participating in a VANET might have on their travel time – assuming that drivers appropriately react to received warnings.

Figure 4 shows that simulated vehicles were able to reach their destination significantly faster if peers informed them of congested roads they encountered while navigating the road network. In fact, travel times in this scenario were often shorter than in the reference scenario where traffic was allowed to flow freely and vehicles did not communicate with one another.

Such bidirectionally coupled simulations can easily be performed on the basis of experimental data, using e.g. road maps and traffic density measurements to closely model real-world scenarios. Serving as the basis for the road layout, we are using map data publicly available from the OpenStreetMap[7] project. A rendered representation of the map data, overlaid with the locations of the individual cars and network connections as

[5] http://www.traffic-simulation.de/

[6] http://www7.informatik.uni-erlangen.de/veins/

[7] http://www.openstreetmap.org/

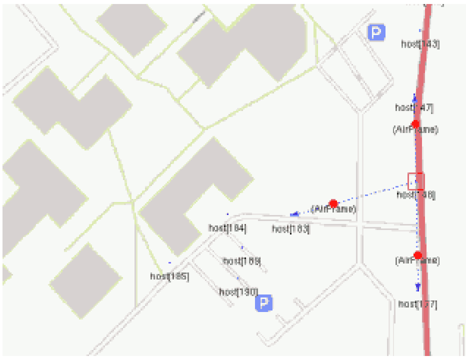


Fig. 5. Use of real-world data in bidirectionally coupled simulations. Model of a university campus running in the OMNeT++ network simulator and the SUMO road traffic simulator.

controlled by the network simulator, is given in Figure 5. This data models a particular section of the required road network in great detail, accurately reflecting road attributes such as road type, access restrictions, lane counts, and speed limits.

IV. Conclusion

As outlined in the historical overview of mobility modeling approaches for VANET simulations, the need for more realistic modeling of car movements is continuously increasing. The main advantage is a more precise analysis of developed VANET protocols and applications. This trend is mainly driven by the availability of improved road traffic microsimulation tools and the demand to study bigger and more complex road scenarios.

Reflecting recent simulation results for VANET protocols based on very different mobility modeling approaches, we demonstrated how more realistic mobility models often lead to vastly different results, and how bidirectionally coupled network and road traffic simulation can open up new possibilities in Vehicular Ad Hoc Network research. It could be shown that the use of more complex mobility models comes at a price in terms of increased simulation runtime. Nevertheless, it can be said, that even with very detailed movement calculations, the amount of computational resources dedicated to road traffic simulation is still quite small compared to that needed for accurate network traffic simulation.

The VANET research community now has openly-available, high-quality tools at its disposal. From the lessons learned from more than a decade of VANET simulation, we strongly advocate to base future studies on such more realistic mobility models.

References

[1] J. J. Blum, A. Eskandarian, and L. J. Hoffman, "Challenges of Intervehicle Ad Hoc Networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 5, no. 4, pp. 347–351, December 2004.

[2] M. Mauve and J. Widmer, "A Survey on Position-Based Routing in Mobile Ad-Hoc Networks," *IEEE Network*, vol. 15, no. 6, pp. 30–39, 2001.

[3] T. K. Mak, K. P. Laberteaux, and R. Sengupta, "A multi-channel VANET providing concurrent safety and commercial services," in *11th ACM International Conference on Mobile Computing and Networking (ACM MobiCom 2005): 2nd ACM International Workshop on Vehicular Ad Hoc Networks (VANET'05)*. Cologne, Germany: ACM, 2005, pp. 1–9.

[4] N. Wisitpongphan, F. Bai, P. Mudalige, V. Sadekar, and O. Tonguz, "Routing in Sparse Vehicular Ad Hoc Wireless Networks," *IEEE Journal on Selected Areas in Communications (JSAC)*, vol. 25, no. 8, pp. 1538–1556, October 2007.

[5] L. Wischhof, A. Ebner, and H. Rohling, "Information dissemination in self-organizing intervehicle networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 6, no. 1, pp. 90–101, March 2005.

[6] D. B. Johnson and D. A. Maltz, "Dynamic Source Routing in Ad Hoc Wireless Networks," in *Mobile Computing*, T. Imielinski and H. F. Korth, Eds. Kluwer Academic Publishers, 1996, vol. 353, pp. 152–181.

[7] European Telecommunications Standards Institute, "Selection procedures for the choice of radio transmission technologies of the UMTS; TR 101 112 V3.1.0 (1997-11)," Tech. Rep., November 1997.

[8] J. Yoon, M. Liu, and B. Noble, "Random waypoint considered harmful," *Twenty-Second Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2003)*, vol. 2, pp. 1312–1321, 30 March - 3 April 2003.

[9] D. R. Choffnes and F. E. Bustamante, "An Integrated Mobility and Traffic Model for Vehicular Wireless Networks," in *2nd ACM International Workshop on Vehicular Ad hoc Networks (VANET 2005)*. Cologne, Germany: ACM, September 2005, pp. 69–78.

[10] J. G. Jetcheva, Y.-C. Hu, S. PalChaudhuri, A. K. Saha, and D. B. Johnson, "Design and evaluation of a metropolitan area multitier wireless ad hoc network architecture," *Mobile Computing Systems and Applications, 2003. Proceedings. Fifth IEEE Workshop on*, pp. 32–43, October 2003.

[11] A. K. Saha and D. B. Johnson, "Modeling mobility for vehicular adhoc networks," in *1st ACM International Workshop on Vehicular Ad Hoc Networks (VANET 2004)*, Philadelphia, PA, USA, October 2004, pp. 91–92.

[12] C. Sommer, I. Dietrich, and F. Dressler, "Realistic Simulation of Network Protocols in VANET Scenarios," in *26th IEEE Conference on Computer Communications (IEEE INFOCOM 2007): Mobile Networking for Vehicular Environments (MOVE 2007), Poster Session*. Anchorage, Alaska, USA: IEEE, May 2007, pp. 139–143.

[13] V. Naumov, R. Baumann, and T. Gross, "An evaluation of inter-vehicle ad hoc networks based on realistic vehicular traces," in *MobiHoc '06: Proceedings of the 7th ACM international symposium on Mobile ad hoc networking and computing*. New York, NY, USA: ACM, 2006, pp. 108–119.

[14] M. Piorkowski, M. Raya, A. L. Lugo, P. Papadimitratos, M. Grossglauser, and J.-P. Hubaux, "TraNS: Joint Traffic and Network Simulator," in *13th ACM Annual International Conference on Mobile Computing and Networking (MobiCom'07)*, Montreal, Canada, September 2007.

[15] C. Sommer, Z. Yao, R. German, and F. Dressler, "On the Need for Bidirectional Coupling of Road Traffic Microsimulation and Network Simulation," in *9th ACM International Symposium on Mobile Ad Hoc Networking and Computing (ACM Mobihoc 2008): 1st ACM International Workshop on Mobility Models for Networking Research (MobilityModels'08)*. Hong Kong, China: ACM, May 2008.

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