Towards Modeling Ad Hoc Networks: Current Situation and Future Direction

---

Citation:

Jiajia Liu, Hiroki Nishiyama, Nei Kato, Tomoaki Kumagai, and Atsushi Takahara, "Towards Modeling Ad Hoc Networks: Current Situation and Future Direction," IEEE Wireless Communications, vol. 20, no. 6, pp. 51-58, Dec. 2013.

URL:

http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6704474

Towards Modeling Ad Hoc Networks: Current Situation and Future Direction

Jiajia Liu*, Hiroki Nishiyama*, Nei Kato*, Tomoaki Kumagai†, and Atsushi Takahara†
*Tohoku University, Sendai, Japan
†NTT Network Innovation Laboratories, NTT Corporation, Yokosuka, Japan

***Abstract*—The last decade has witnessed a tremendous increase in both the number of mobile devices and also the consumer demand for mobile data communication. As a consequence, networking technologies are shifting from traditional highly centralized towards future organically distributed so as to meet such great demand. As the most general networking architecture, ad hoc network has long been regarded as the most challenging to design and quantify, due to the possible hybrid component settings and heterogeneous node behaviors there. Towards this end, we review the current state-of-the-art of analytical models and techniques developed for performance analysis in ad hoc networks. Specifically, we discuss modeling techniques related to the fundamental topics in ad hoc network research, namely, node mobility, wireless interference, node spatial distribution, and information delivery process. Besides discussions of advantages and limitations of available models, promising future research directions are also outlined.**

***Index Terms*—Ad hoc networks, performance modeling, mobility, interference, spatial distribution, delivery process.**

I. INTRODUCTION

The last decade has witnessed a tremendous increase in both the number of mobile devices and also the consumer demand for mobile data communication. According to the latest statistics [1], the number of mobile-connected devices would increase beyond the world's population by the end of 2012 and will become 10 billion in 2016, almost 1.4 mobile devices per capita. The average speed of mobile connection will exceed 1 Mbps in 2014, and from 2011 to 2016 the average annual growth rate of mobile data traffic will be around 78 percent. Furthermore, the worldwide mobile data traffic per month will exceed 10 exabytes by 2016, among which the amount generated by tablets (1.1 exabytes) will almost equal that of global mobile data in 2012.

Such massively growing demand for wireless communications is driving us into a challenging dilemma. Facing the skyrocketing number of mobile users and their sharply rising needs for ubiquitous wireless connectivity and internet access, we have only limited wireless band resources. Relying solely on traditional centralized networking architectures cannot meet the great demand. Towards this ends, academia, industries, standard bodies, and governments have devised a lot of proposals and promising techniques, such as cognitive radio, white space, Femtocells, D2D communications, etc. From these techniques, one can easily see that the general trend of networking technologies is evolving from traditional highly centralized towards future organically distributed.

Under this general trend, all the current and future networks will be organized into a huge distributed ad hoc network via the Internet backbone connection, including the spatial satellite networks, above-ground cellular networks, mobile ad hoc networks, vehicular ad hoc networks, WiMAX networks, Hotspot networks, body area networks, etc. In such a huge hybrid and heterogeneous ad hoc network, including infrastructure-based and self-organized communications, static and mobile users, resource-sufficient and resource-constrained users, selfish and altruistic users, etc., there are lots of problems which are presently unexplored. For example, what are the possible achievable performances for any node pair there? What is the best performance that we can achieve with our current networking technology? What are the fundamental limits in the ultimate future of utilizing wireless channel? To thoroughly understand the general ad hoc network is a long-term challenging task, what we have obtained by now are only for very limited special cases.

Researchers from all over the world have been racking their heads for possible solutions to the above challenging problems. Obviously, simulations and experiments, although good at the part of validation and confirmation, can never provide us the desired answers. The only way to figure out the answers, is to develop solid analytical models and mathematical techniques. Just as the well-known Shannon theory has been indispensable for modeling and designing of the current mature point-to-point communication systems, analytical models and techniques will serve as important guidelines for the implementation, development, and optimization of future ad hoc networking technologies. Specifically, they can encourage large investments in developing communication technologies by providing plausible performance targets, and also present a clear roadmap to numerous communication engineers by indicating whether a performance target is physically possible or impossible, what is the improvement that is still possible to make via efforts under the current manufacturing technologies, what is the necessary cost one has to tolerate when achieving a specified target, etc.

In this article, we review the current state-of-the-art of analytical models and techniques developed for performance analysis in ad hoc networks. Specifically, we discuss modeling techniques related to the fundamental topics in ad hoc network research, namely, node mobility, wireless interference, node spatial distribution, and information delivery process. Then, we point out some promising future research directions. Note that node mobility and node spatial distribution are closely related to the geometric feature in mobile ad hoc networks and that in static ad hoc networks, respectively; while wireless interference represents another dimension and exists in both mobile and static ad hoc networks; information delivery process, the very essence of networking communications, is complicated enough to involve all possible research topics. Besides these four topics, there exist a lot of other topics that merit to be investigated, such as the route/link dynamics, channel assignment, medium access, etc.

The rest of this article is organized as follows. We introduce node mobility modeling in Section II, and discuss interference modeling in Section III. Sections IV and V are dedicated to the modeling techniques of spatial distribution and delivery process, respectively. Finally, we summarize this article and discuss some future research directions in Section VI.

II. NODE MOBILITY MODELING

Node mobility affects significantly the achievable performances in a wireless ad hoc network. When it comes to exploring the fundamental performance limits in an ad hoc network or to determining whether or not a proposed protocol will improve the network performances, the first priority is to select a mobility model that can accurately represent the movements of mobile nodes deployed in the network area. Currently, there are two types of mobility models widely adopted in ad hoc network research, i.e., realistic trace-based mobility models and synthetic mobility models.

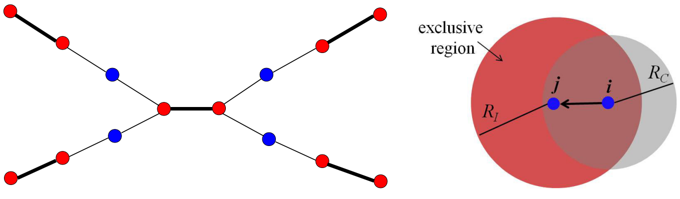
Realistic trace-based mobility models are usually used to experimentally study the performances of network protocols. The biggest advantage of trace-based model lies that it could provide an accurate description of how node location and moving velocity vary over time in the sampling area, especially when the collected mobility traces involve a large number of mobile nodes and a long enough sampling period. However, one common limitation of trace-based models is that it is very difficult to adopt them for developing theoretical framework or conducting analytical evaluation. Also, the application of collected traces could be limited, since the node trace may change dramatically when deployed in different areas. Furthermore, collecting mobility traces is usually costly and sometimes even impossible if the network is to be established in some extremely challenging environments.

In light of the above limitation of trace-based mobility models, it is necessary to use synthetic mobility models to mimic the node movements in ad hoc networks. Available synthetic models can be divided into two classes. The first class are the entity mobility models where the node movements are identically distributed and independent of each other, like the Random Walk model, Random Waypoint model, Random Direction model, Brownian mobility, home-point mobility model, Levy walk model, etc. The second class are the group mobility models where the movements of nodes are correlated to each other, such as the Reference Point Group Mobility model, the Pursue Mobility model, Nomadic Community model, Column Mobility model, etc. Recently, it was reported that Levy walk model and human walk patterns contain statistically similar features including heavy-tail flight distribution, pause-time distribution, and the super-diffusive nature of mobility, based on 226 daily GPS traces collected from 101 volunteers in five different outdoor sites [2]. Please refer to [3] for definitions of these synthetic mobility models.

We discuss here some interesting advanced features pertaining to synthetic models, which have been validated to be very useful for analytical evaluation of ad hoc network performances. First, we introduce the independently and identically distributed (i.i.d.) mobility model, under which the mobile nodes are uniformly and randomly distributed in the network area and the nodes are totally reshuffled at each time slot (or instant). The i.i.d. model has three advantages: firstly, it is very helpful to keep the theoretical analysis tractable and enables closed-form analytical expressions to be derived for ad hoc networks; secondly, as the network topology varies so dramatically that the node behavior can never be predicted under the i.i.d. model, the performance analysis developed under such model could provide a meaningful bound in the limit of infinite mobility; thirdly, it is shown that the network performances derived under the i.i.d. model, such as the throughput capacity, the end-to-end delay, the delivery delay, and the delivery probability, etc., are actually identical to those observed under other non-i.i.d. mobility models (like the Markovian Random Walk model and Random Waypoint model) if they follow the same steady state channel distribution [4].

Another interesting feature that has been widely adopted for performance analysis of ad hoc mobile networks is that, in a closed network region, the time elapsed between two consecutive contacts of any node pair follows an exponential distribution, i.e., the occurrence of contacts between any two mobile nodes follows Poisson distribution. In [5], the exponentially distributed inter-meeting time was first reported and validated to hold for the Random Waypoint model, Random Direction model, and Random Walk model, etc. Later, La *et al.* showed in [6] that even under the generalized Hybrid Random Walk mobility model which covers a lot of synthetic models as special cases, the distribution of inter-meeting times can also be well approximated with an exponential distribution.

Node mobility modeling is a long term fundamental problem in ad hoc network research. Note that all the synthetic models mentioned above assume homogeneous patterns for all mobile nodes, and thus fail to characterize the heterogeneous node movements in the actual ad hoc networks. It is also noticed that the available synthetic models can only be used to capture various characteristics of node mobility to somewhat "realistic" extent. Therefore, how to devise a general mobility model that matches best with the realistic mobility traces while simultaneously keeps the tractability and feasibility of theoretical analysis remains a challenging problem. Another future research direction could be to abstract more advanced features of available mobility models, like the i.i.d. feature and exponentially distributed inter-meeting time, so as to facilitate theoretical analysis and thus improve our understanding of various performance limits in ad hoc networks.



(a) (b)

Fig. 1. (a) Example of the 2-hop interference model where the thick links between the red nodes can be simultaneously activated. (b) Illustration of the interference range model where node i is transmitting to node j, R_C and R_I denote the communication range and the interference range, respectively.

III. WIRELESS INTERFERENCE MODELING

Consider a wireless link in an ad hoc network where the transmitter is transmitting packets to the receiver. Due to the complicated effects of path loss, shadowing, and fading, the wireless signal arriving at the receiver is actually an attenuated and distorted version of the original modulated signal radiated by the transmitter. Whether the signal received at the receiver can be successfully demodulated (i.e., whether the packets can be successfully received) depends not only on the desired signal strength but also on the thermal noise power and the levels of vicinal on-going signal transmissions in the operating frequency channel throughout the whole duration of packet transmission. If the other on-going signals (i.e., the interferences) received at the receiver are too strong at any single point during the packet transmission, the packet cannot be successfully received and an outage happens. An accurate modeling of such basic phenomenon serves as a core role in the analysis and optimization of ad hoc network performances. Towards this end, a variety of wireless interference models have been proposed to characterize the impacts of interferences and specify the conditions under which the signal received at an intended receiver can be successfully demodulated.

We introduce the popular wireless interference models from simple to sophisticated. To simplify the expression, hereafter we assume all nodes are operating in the same frequency channel. The first interference model to be introduced is the K-hop interference model, under which any two wireless links of distance less than K-hops cannot transmit simultaneously. In other words, in order to guarantee the successful data reception at an intended receiver, any other node that has a distance of less than K hops from the transmitter or the receiver, should keep silent during the data transmission. Actually, a large number of network systems can be modeled by the K-hop interference model. For example, the 1-hop interference model, also known as the primary or node exclusive interference model, can be applied to the FDMA or CDMA based ad hoc networks, where multiple frequencies or codes are adopted for interference avoidance and each node is equipped with a single transceiver. The 2-hop interference model is widely used for the IEEE 802.11 based wireless networks. Specifically, it corresponds to the communication modeling under the RTS/CTS based IEEE 802.11 DCF (Distributed Coordination Function), where the transmitter and the receiver exchange RTS and CTS messages before data transmission so as to block the neighboring nodes within one-hop distance. Fig. 1a illustrates an example of 2-hop interference model.

Besides the above hop-based interference model, there is distance-based interference model: interference range model [7]. Under such model, a node has a successful packet reception provided that, the distance from it to the transmitter and that from it to any other interfering transmitter satisfy the given requirements. Specifically, according to the interference range model, in order for a wireless link to have successful packet transmission, we should have: 1) the distance between the receiver and the transmitter is no greater than the communication range; 2) the distance from the receiver to any other interfering transmitter is no smaller than the interference range. As shown in Fig. 1b, in the interference range model, the interference range is used to define the exclusive region around the receiver wherein no other simultaneous transmitters are allowed. A special case of the interference range model is the popular Protocol model, which requires the interference range to be $1+\Delta$ times the distance from the transmitter to the receiver, with Δ denoting a fixed positive guard factor.

There are also two kinds of signal power-based interference models, i.e., the capture threshold model and the physical model. The capture threshold model which is used in the simulation tools like *ns2*, assumes two threshold requirements to determine successful packet transmission for a wireless link: 1) the desired signal power received at the receiver should be no smaller than the receive threshold *RxThresh*; 2) the ratio of the desired signal power received from the transmitter to the signal power received from any other single interfering transmitter should be no smaller than the capture threshold *CpThresh*. Distinguished from the capture threshold model, the physical model takes into account the additive interference from all other simultaneous transmissions. In order to ensure a successful packet reception, it is required that during the whole packet transmission, the SINR (Signal to Interference and Noise Ratio) perceived by the receiver should be no smaller than a specified threshold value, which achieves negligibly small packet error rate (PER).

As introduced before, it is of fundamental importance to develop accurate interference models so as to provide careful characterization of the wireless interference effects in ad hoc network communications. Among the five wireless interference models discussed above, the hop or distance based interference models or the capture threshold interference model, although simple and easy to use, fail to consider the additive interference effects as observed in the actual ad hoc networks. Furthermore, it was reported that such kind of simplifications may result in significant overestimation or underestimation of network performances, and sometimes even predict totally different qualitative network behaviors. On the other hand, the physical model which considers all the possible interferences and noise, is difficult to be employed for network simulation, performance analysis or optimization, especially as the network size scales up. It is further noticed that in order to simplify the analysis and keep it tractable, available physical model based works usually assumes for all nodes the same setting of network parameters, like the transmit power, the channel distribution, the modulation and coding schemes, etc. Much more works is needed on consideration

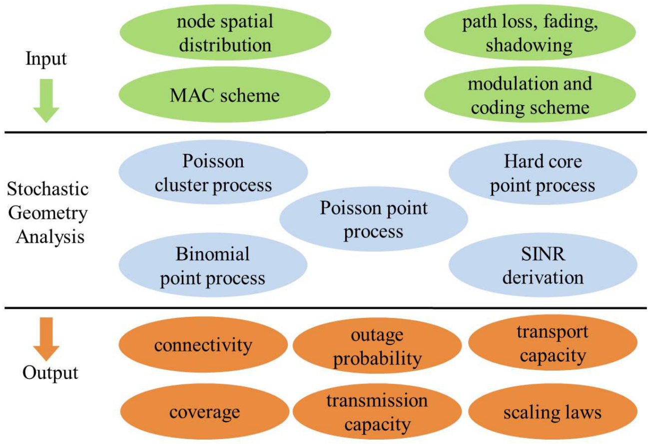


Fig. 2. Illustration of applying stochastic geometry to the spatial modeling and analysis of ad hoc networks.

of the heterogeneity in realistic ad hoc networks, design of simple yet efficient interference models, confirmation of the accuracy of available models in various scenarios, and further exploration of conditions under which the available models are most suitable to be adopted, i.e., without resulting in any appreciable loss of accuracy.

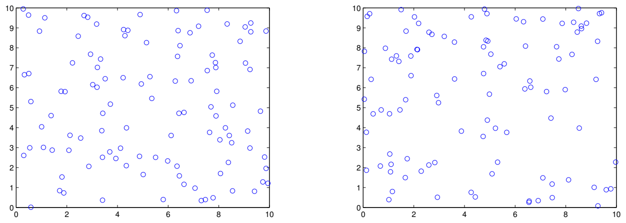
IV. SPATIAL DISTRIBUTION MODELING

Different from previous point-to-point communication systems, ad hoc networking communications are fundamentally limited by the performance metric of SINR perceived at each node in the network. Suppose node i is transmitting to node j, and denote by $\Psi(i)$ the set of nodes transmitting simultaneously in the same frequency channel as i, then the SINR at j can be given by

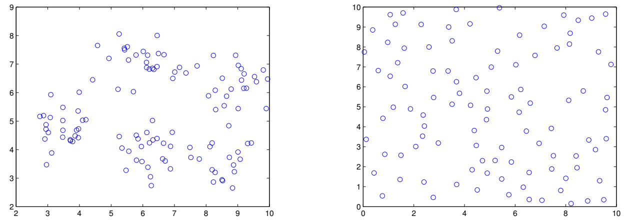
$$SINR = \frac{P_i h_{ij}}{\sum_{k \in \Psi(i)} P_k h_{kj} + \sigma^2},$$

where P_i and h_{ij} denote the transmit power of i and the channel gain between i and j, respectively, and σ^2 is the noise power.

Note that among the components that determine the SINR metric, the received strength of intended signal and the level of surrounding interferences at a node, depend on a lot of factors which is usually unavailable at the node, such as the set of interfering nodes, i.e., the nodes selected by the MAC (Medium Access Control) scheme to transmit concurrently, their locations, channel status, and transmit power, etc. It is further noticed that these complicated uncertain factors are actually closely related to the underlying network geometry, i.e., the spatial distribution of nodes in the network region. However, the traditional communication theories appear insufficient when applied to account for the randomness of geometrical configuration in general ad hoc networks. In this section, we introduce a useful mathematical technique, i.e., stochastic geometry [8], which has been proved to be very helpful in gaining a deeper understanding on the randomness of node spatial distribution and studying the average network behaviors, like the connectivity, coverage, outage probability, transmission capacity (or area spectral efficiency), transport capacity, and their scaling laws, etc. Fig. 2 shows an example of the role that the stochastic geometry theory plays in ad hoc network research.



(a) Poisson point process (b) Binomial point process



(c) Poisson cluster process (d) Hard core point process

Fig. 3. Four sample point processes. The Poisson point process has an average node density of 1, whereas the number of nodes in the Binomial point process is fixed as 100, the number of clusters in the Poisson cluster process is selected as 5, and the minimum inter-node distance in the Hard core point process is chosen as 0.5.

Since the network geometric configuration (or topology) has a fundamental impact on the performances of ad hoc networks and the spatial distribution of nodes in a network region may vary widely over a very large (often infinite) probability space, it is rather limited to analyze or optimize the network performances for a specific spatial distribution. Instead, one should adopt a statistical distribution to model various geometric configurations and then obtain statistical averages for the performance metrics via stochastic geometry. In this article, we discuss the intrinsic core part of stochastic geometry, i.e., the point process, rather than go deep into the details of applying stochastic geometry analysis to study and derive various performance metrics. For a survey of research on this line, see [9].

The popular point processes that have been widely adopted for spatial modeling are as follows:

- Poisson point process (PPP): PPP is the simplest and also the most common spatial model due to its analytical tractability. Since nodes under the PPP model are independently and identically distributed in the given region, it can be directly applied to ad hoc networks with randomized channel access. Fig. 3a shows an example of PPP where the average node density is fixed as 1.
- Binomial point process (BPP): distinguished from a homogeneous Poisson process in which the average node density is specified, under the BPP the number of nodes is fixed for a given region. Therefore, BPP fits well into scenarios where a known number of nodes (mobile or not) are randomly deployed in a cell or area of known size. Fig. 3b represents an example of BPP for 100 nodes

in a 10×10 square.

- Poisson cluster process (PCP): nodes are grouped into clusters and the cluster locations follow the Poisson process. PCP is most suitable for various network scenarios where nodes are located in groups, static or mobile, such as moving troops in battlefield, attendee movements in exhibitions, Femtocell or hotspot users in homes, offices, restaurants, and airports, etc. Fig. 3c shows an example of 5 clusters.
- Hard core point process (HCPP): HCPP is also known as inhibition process. A special feature pertaining to HCPP is the specified minimum inter-node distance, i.e., it prohibits any node pair to coexist if the distance between them is less than a certain value. Due to such feature, HCPP can nicely model the spatial distribution of simultaneous transmitters in wireless networks with carrier sensing and collision avoidance, such as IEEE 802.11 DCF. As shown in Fig. 3d, the minimum inter-node distance there is chosen as 0.5.

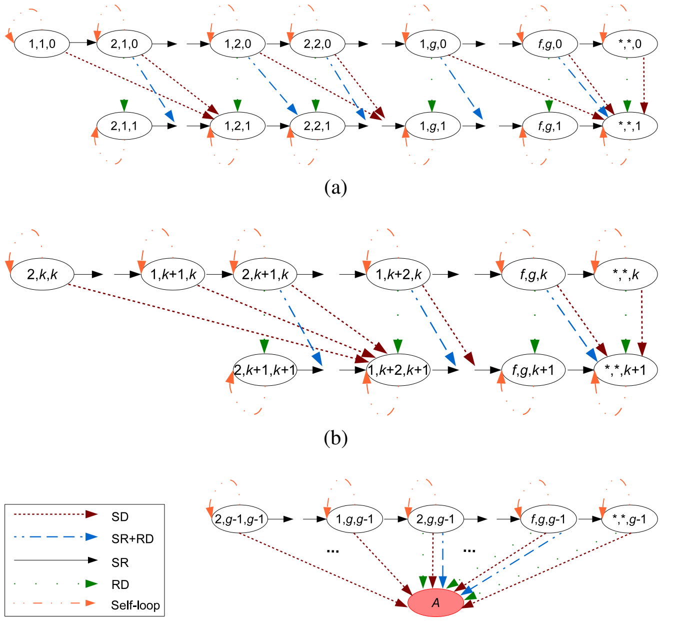
One can also use the combination of above basic point processes to model more sophisticated scenarios in actual networks. For example, the spatial distribution of primary and secondary users in cognitive radio networks can be modeled by the superposition of two independent PPPs, while the spatial distribution of Femtocells and the associated users can be characterized by a proper combination of PPP and PCP [10].

In a realistic ad hoc network, obviously, a node may have no ways to ascertain accurately the locations of other nodes that its ongoing packet transmission will interfere with or get interfered by. By modeling the spatial node distribution with a convenient point process, stochastic geometry enables us to analyze networks with random topologies, and provides statistical averages for a variety of performance metrics via studying a typical node or link. As large amount of research in this line focused on wireless networks with single transceiver or omni-directional antenna, much more works is needed on the settings of multi-antenna beamforming, interference cancellation, or directional antenna. It is noticed that whenever a node increases its transmit power to improve the desired signal strength, it unavoidably incurs more interference at other simultaneous transmissions which are unknown to itself. Therefore, another interesting future direction is to integrate game theory with stochastic geometry, so as to explore the possible performance trade-offs, various statistically optimum performances and corresponding per node strategies.

V. DELIVERY PROCESS MODELING

Based on proper characterization of the fundamental issues of mobility, interference, and spatial distribution, we are able to move a step closer to modeling the challenging issues in ad hoc network research, such as the information delivery process. Delivery process modeling addresses how the information is flowed from the source to the destination, which usually takes multi-hop transmissions in the general ad hoc networks.

For the case that all nodes are static, the end-to-end information delivery process mainly relies on the traffic pattern injected to the network, the underlying MAC scheme, and the upper layer scheduling and routing schemes. Depending on the amount of network information available to the node at each hop, such as the queue backlogs at neighboring nodes, their channel status, remaining power, etc., the node can make a sub-optimal or optimum decision so as to achieve the maximum throughput (or the capacity region), the minimum delivery delay, or efficient throughput-delay trade-offs for elastic or inelastic traffics. Some well-known policies have been developed in literature, such as the greedy scheduling, the maximum-weight scheduling, the back-pressure routing, or other cross-layer scheduling and Lyapunov drift based optimum control schemes. There is a large amount of ongoing research works in this line, see [11] for a taxonomy.



(a)

(b)

(c)

Fig. 4. Markov chain model for delivery process of a group of packets under the 2HR-(f, g) routing, where SD, SR, and RD corresponds to source-to-destination, source-to-relay, and relay-to-destination transmissions, respectively. (a) denotes the state transition diagram when no more than one packet is received by the destination. (b) represents the cases that the destination may receive at most one more fresh packet given that it has already received k packets of the tagged group. (c) shows how the destination receives the last packet.

As the network nodes may have very limited resources, like power energy and storage space, each node hopes to maximize its own utility or payoff. According to its buffer occupation, queue backlogs, remaining power energy, QoS requirements or utility functions, a node participating the information delivery process may be able to freely adjust its network behaviors, such as controlling the transmit power, switching the operating channel, opportunistically transmitting packets from different traffic flows or dropping exogenous arriving packets. In such cases, there may exist a lot of competition games where the game theory can be well applied to find the possible Nash equilibrium, the Pareto optimal Nash equilibrium, and the corresponding best performances. Please refer to [12] for a survey on game theory applications in wireless networks.

Regarding mobile ad hoc networks (MANETs), due to the random node mobility, the network topology varies dramatically and no contemporaneous end-to-end routing path may ever exist at any given time instant. The information delivery usually relies on the cooperation of relay nodes, i.e., the message (or data) is delivered in a store-carry-forward way. Considering the random node contacts, short contact duration and limited information that can be transmitted during each contact, the delivery process of a message with general size or limited lifetime could become very complicated, especially under the realistic MANET settings. Some analytical models have been developed to characterize the delivery process in MANETs, like ODE (ordinary differential equation) based models and fluid approximation based models. However, due to the common assumption that every time two nodes meet together they can transmit with each other, these models can only be well applied in the scenarios, like delay tolerant networks (DTNs) and intermittently connected mobile networks (ICMNs), where nodes are so sparsely distributed that the interference and medium contention issues can be therefore neglected. For the general MANETs in which the medium contention, interference, and traffic contention issues are of significant importance, we introduce here the general absorbing Markov chain based modeling technique, which enables a careful consideration of all above important issues and also tractable theoretical framework for derivations of various performance metrics in closed-form expressions.

An absorbing Markov chain consists of multiple transient states and absorbing states, where an absorbing state represents termination of the information delivery process. From any transient state it is possible to enter an absorbing state within one or several steps. According to the underlying time system, the absorbing Markov chain can be further defined as follows: 1) it is called as discrete-time absorbing Markov chain (DTMC) if time is divided into slots of equal duration. For a DTMC, one needs to define the one-step transition probabilities among transient states and absorbing states during each time slot. The sum of all one-step transition probabilities from each transient state equals one in a DTMC. 2) it is called as continuous-time absorbing Markov chain (CTMC) if continuous time system is used. For a CTMC, one needs to define the transition rate from a transient state to another transient state or absorbing state. Note that in a CTMC, the transition rate from each transient state back to itself is always negative, and the sum of all transition rates from each transition state equals zero. Actually, for a given CTMC, there always exists a DTMC embedded just before the jumping time of each transient state in the CTMC.

As discussed before, the absorbing Markov chain technique can be applied to model the information delivery process for the general MANETs and enables derivations of various performance metrics in closed-form expressions, such as throughput capacity, end-to-end delay, delivery delay (both the mean value and the variance), delivery cost, delivery probability, etc. Here we take the general group-based two-hop relay routing (i.e., 2HR-(f, g)) introduced in [13], as example to show how to develop Markov chain model. According to the 2HR-(f, g) routing, packets are divided into consecutive groups at the source, g packets per group. The source replicates each packet to at most f distinct relay nodes, and the destination accepts a packet as long as it is fresh and also among the packet group currently under requesting. For a tagged packet group, if we use A to denote an absorbing state that the destination receives all the g packets, use (i, j, k) to denote a transient state that the source is delivering the i_{th} copy for the j_{th} packet while the destination has received k packets, and use $(*, *, k)$ to denote a transient state that the source has dispatched the copies of all g packets while the destination receives only k of them, then the delivery process of the tagged packet group can be defined by the Markov chain shown in Fig. 4. For details of derivations for various performance metrics, please refer to [13] and references therein.

Basically, as long as a delivery process satisfies the fundamental Markov property, it can be modeled by the Markov chain technique. However, the tractability of a theoretical framework usually comes after simplifying or neglecting of some trivial behaviors in practice. A fine-grained definition of transient states in Markov chain models, although able to provide a better characterization of the actual delivery process, unavoidably results in sharp rise of the problem state space, which may cause the theoretical framework to become intractable. Therefore, one needs to make a careful trade-off between the problem state space and the modeling deviation (i.e., the gap between the theoretical approximation and the actual value). Specifically, one needs to properly define absorbing states and transient states which could nicely match the actual delivery process and simultaneously keep the whole theoretical framework tractable, so as to facilitate the derivations of transition rates or transition probabilities.

In order to further elaborate on selections of modeling techniques, in the following, we take the scenario of vehicular ad hoc communication as an example. When it comes to evaluating the performances of a protocol newly proposed for vehicular ad hoc communications, one may adopt specific mobility models incorporating real street map data and speed limit information unique to the particular geographical area that might be the target for the deployment of the protocol; when it comes to developing theoretical frameworks for analytical study, one may adopt Random Waypoint model to approximate the mobility behaviors of vehicles. As vehicles communicate to each other while moving on streets, one can adopt the K-hop interference model to address the interference issue there, after properly tuning the parameter K according to the system settings such as transmit power, average mutual distance, etc. Depending on the per vehicle behavior (resp. the property of adopted protocol), one may adopt game theory (resp. absorbing Markov chain) to model the corresponding information delivery process.

VI. CONCLUSIONS

For the last several decades, ad hoc network has been regarded as the most general and challenging networking architecture in terms of design and quantification. In this article, we have reviewed the state-of-the-art analytical models and techniques for performance analysis in ad hoc networking communications, from the perspectives of node mobility, wireless interference, spatial distribution, and information delivery process. The available models, due to their intrinsic assumptions, are either easy to use but fail to capture the heterogeneous node behaviors in realistic ad hoc communications, or difficult to adopt for derivations of tractable theoretical framework. Therefore, much more works is needed, on abstracting more advanced features of available models to facilitate mathematical derivations, and further application of these models in various network scenarios to gain deeper understanding of both their advantages and limitations.

While the available models have been proved to hold nicely in some scenarios, they are still far from sufficient to address the future general ad hoc networks. To characterize the most general hybrid and heterogeneous ad hoc network, one needs to first dig out the most fundamental principles that govern the communications in ad hoc networks, and then design new models or techniques to nicely capture these fundamental principles. Meeting this challenge requires new ideas, new analytical tools, fundamental mathematics beyond the confines of traditional communication and information theories, and even methodologies from other networking related fields, like economics, biology, and thermokinetics. Future research should be focused on developing inter-discipline models, to integrate tools and methodologies from traditional communication and information theories along with optimization, control, stochastic process, game theory, combinatorics, statistics.

REFERENCES

[1] Cisco, “Cisco visual networking index: Global mobile data traffic forecast update, 2011-2016,” White Paper, February 2012.

[2] I. Rhee, M. Shin, S. Hong, K. R. Lee, S. J. Kim, and S. Chong, “On the levy-walk nature of human mobility,” *IEEE/ACM Transactions on Networking*, vol. 19, no. 3, pp. 630–643, June 2011.

[3] T. Camp, J. Boleng, and V. Davies, “A survey of mobility models for ad hoc network research,” *Wireless Communications & Mobile Computing*, vol. 2, pp. 483–502, 2002.

[4] J. Liu, X. Jiang, H. Nishiyama, and N. Kato, “On the delivery probability of two-hop relay manets with erasure coding,” IEEE Transactions on Communications, 2013, published online.

[5] R. Groenevelt, “Stochastic models in mobile ad hoc networks,” Ph.D. dissertation, University of Nice Sophia Antipolis, April 2005.

[6] R. J. La, “Distributional convergence of inter-meeting times under generalized hybrid random walk mobility model,” *IEEE Transactions on Mobile Computing*, vol. 9, no. 9, pp. 1201–1211, September 2010.

[7] A. Iyer, C. Rosenberg, and A. Karnik, “What is the right model for wireless channel interference,” *IEEE Transactions on Wireless Communications*, vol. 8, no. 5, pp. 2662–2671, May 2009.

[8] D. Stoyan, W. S. Kendall, and J. Mecke, *Stochastic geometry and its applications: 2nd Edition*. John Wiley and Sons, 1996.

[9] M. Haenggi, J. Andrews, F. Baccelli, O. Dousse, and M. Franceschetti, “Stochastic geometry and random graphs for the analysis and design of wireless networks,” *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 7, pp. 1029–1046, September 2009.

[10] J. G. Andrews, M. Haenggi, N. Jindal, and S. Weber, “A primer on spatial modeling and analysis in wireless networks,” *IEEE Communications Magazine*, vol. 48, no. 11, pp. 156–163, November 2010.

[11] Stochastic network optimization. [Online]. Available: http://www-bcf.usc.edu/~mjneely/stochastic/index-old.html

[12] M. Felegyhazi and J.-P. Hubaux, “Game theory in wireless networks: A tutorial,” Technical Report LCA-REPORT-2006-002, EPFL, February 2006.

[13] J. Liu, X. Jiang, H. Nishiyama, and N. Kato, “Generalized two-hop relay for flexible delay control in manets,” *IEEE/ACM Transactions on Networking*, vol. 20, no. 6, pp. 1950–1963, December 2012.