Mobile social networks and dynamic spectrum demand: models and applications

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Abstract

Models of mobile social networks and wireless spectrum demand are useful in optimizing the performance of hybrid wireless networks, as well as for applications such as spectrum market trading and understanding cascading failures in inter-dependent infrastructures. These are commonly modeled by simple stochastic processes, which do not adequately capture key aspects of real systems. Here, we discuss a first-principles based approach for developing synthetic mobile social networks and spectrum demand models, and two applications of it on urban-scale networks. Some of the key challenges for our approach include: (i) the computational issues in processing very large complex networks of urban populations, and (ii) statistical and data mining issues in modeling and validation.

1 Introduction

Advances in radio and communication technology have led to diverse kinds of large-scale wireless networks, such as cellular, wifi and ad-hoc networks, and users now expect ubiquitous network support. The performance of protocols on such systems depends crucially on the structure of the underlying dynamic network and traffic [1]. These networks show significant spatio-temporal variation, and cannot be adequately modeled by simple stochastic processes, such as random waypoint models [7], which are used extensively. Therefore, realistic models of mobility and spectrum demand are needed in order to optimize these protocols and operate the network close to its capacity.

New applications in recent years have led to increased interest in realistic mobility and spectrum demand modeling. The first is cognitive radio networks and spectrum trading – because of advances in cognitive radio technology, wireless devices are increasingly able to sense and switch power levels and channels very efficiently. This has led to proposals to open up licensed spectrum bands for use by unlicensed secondary users (SU), as long as the disruption for licensed primary users (PU) is minimized. This requires a high-resolution modeling of spatio-temporal spectrum demand at an urban scale, in order to help predict and identify safe spectrum blocks for SUs. The FCC is also considering proposals for trading spectrum at various levels and time scales. As in the case of the deregulation of electrical markets, there is always a risk of collusion between players, which might result in inefficient markets, thereby defeating the goal of deregulation. Studying different market mechanisms and identifying potential issues is an important requirement for such dynamic spectrum auctions. Such a study requires effective market simulation tools that can reveal the dynamics of different auction mechanisms, and enable efficient design.

The second application where such models are necessary is in the analysis and response to emergencies and cascading failures in infrastructure networks. Emergency events, including natural disasters such as floods and storms and man-made ones such as explosions and spills entail evacuations from large urban regions, which impacts different infrastructures, such as the road transport, power and communication

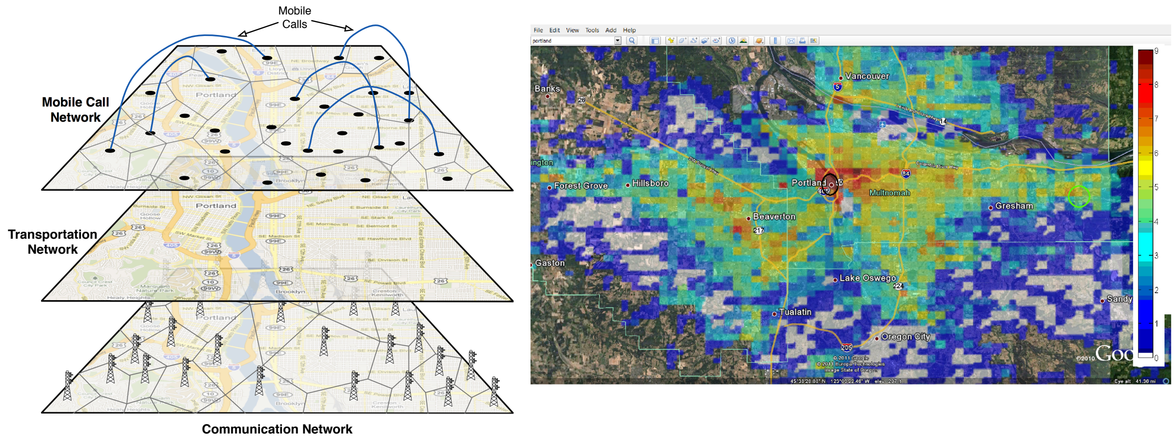

Figure 1: (a) Interdependencies between multiple infrastructures, which need to be modeled together. (b) Model of spectrum demand for Portland, OR.

infrastructures. Advances in cyber-based systems and communication infrastructure have coupled these systems – this has, on one hand, made many of the systems more robust and efficient, while on the other hand, this has introduced new vulnerabilities in these interdependent systems. Failure in one system can cascade and cause failures in other coupled systems. We call such cascades *co-evolving cascades in interdependent infrastructures*. Cellular networks play a significant role during such evacuations in coordination and response. This changes the spectrum demand pattern, which could overload the system and cause significant disruptions in service. Understanding and planning for such events requires not only a model of the normative mobility and spectrum demand pattern, but a framework to study the impact of behavioral and coupled effects. Further, multiple social and infrastructure networks need to be coupled, as illustrated in Figure 1(a).

A common approach in network and traffic modeling has been to use stochastic processes that can match aggregate characteristics of the real networks [7]. However, a number of researchers (e.g., [8]) have pointed out significant problems with such simplified models. Li et al. [8] suggest the need for "first principles" approaches for realistic network and traffic modeling. Due to proprietary, privacy and competitive market reasons, no single integrated data set on wireless traffic is currently available. Nevertheless, a number of different data sets and models (e.g., for urban traffic mobility, device ownership, and calling patterns) exist, which contain partial information about different aspects of the mobile network traffic discussed above. These partial and often noisy data sets can be integrated using indirect procedural and expert knowledge based on sound social and behavioral theories.

In this poster, we describe a first principles approach for developing synthetic yet realistic spatial, dynamic, relational networks for digital traffic modeling at large urban scales. We illustrate the utility of this framework through two applications – the first involves the analysis of primary market mechanisms and the second involves the analysis of the changes in spectrum demand due to cascading effects during an evacuation. We discuss these results in more detail below.

1. Framework for mobile social networks and dynamic spectrum demand ([6]). Our framework produces a spatio-temporal model of movement and call pattern of people in an urban region at highly resolved scale. Our approach involves the following steps:

1. Constructing a synthetic population and traffic model using the methodology from [4, 2] – this combines a number of different data sets, such as census, land use and activity surveys with social theories in order to produce a population that is statistically similar to the census. Routing and interpolation methods are then used to construct space-time trajectories for each person.

2. Modeling device ownership – this involves modeling the number and kinds of wireless and wireline devices used by each person, and is based on a data set from CDC (see [6]).

3. Modeling dynamic spectrum demand – this involves creating a model of call patterns by all individuals in the population who have wireless or wireline devices. This is based on aggregate statistics of call arrival rates, call durations, number of calls and homophilies among callers and callees. We also model the call graph properties, in addition to the spectrum demand.

A snapshot of the spectrum demand produced by our model for Portland, OR, is shown in Figure 1(b). As the figure shows, there is significant spatio-temporal variation in the spectrum demand.

2. Application: wireless spectrum markets ([5]). We couple the dynamic spectrum model with Sigma-Spectrum, a microscopic agent based simulation tool for trading spectrum in wireless markets; this tool models different kinds of players in the primary and secondary markets (providers and speculators), different market clearing mechanisms, and the flow of bids, asks and the allocation of licenses (see [5] for more details). Allowing for potential future trading in a secondary market, we study the impact of various bidding behaviors on the primary market dynamics. Our initial results suggest that such a resale option can attract speculators to the primary market, and we find that speculators can significantly influence the winning price in the primary market. Also, if a few bidders collude and make their bids jointly, the collusive behavior can be rewarding for all the bidders. Our analysis should be seen as a cautionary note for the regulating authorities and the policy makers. It suggests that changes in the assumptions and bidding behavior can significantly alter the market dynamics in unexpected ways, motivating the need for such an approach.

3. Application: cascading failures in interdependent infrastructures ([3]). We study the impact of a chemical plume in a densely populated urban region, which leads to an evacuation of the affected area – this changes the usual activity patterns as people are forced to drive home or to evacuation shelters. They use the wireless networks for coordination among family members and information sharing. These two behavioral adaptations, cause flash-congestion in the urban transport network and the wireless network. We analyze how extended periods of unanticipated road congestion can result in failure of infrastructures, starting with the servicing base stations in the congested area. We also explore the impact of additional failures in the road network (e.g., because of road closures) on the cellular network support. Finally, we study the criticality and robustness of the various base stations and measure how congestion in the transportation network impacts communication infrastructure. Such a study crucially requires realistic models of mobility and spectrum demand, as well as a framework to study the impact of different kinds of changes in user behavior.

The key challenges in our approach include the following: (i) urban-scale social networks are large and unstructured, leading to significant computational challenges. Case studies typically involve a large number of samples, which compounds the computational overhead. (ii) Modeling and validation are significant challenges in such an approach, and standard techniques developed for physical systems do not extend to such systems.

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References

[1] F. Bai, N. Sadagopan, and A. Helmy. Important: a framework to systematically analyze the impact of mobility on performance of routing protocols for adhoc networks. In *IEEE INFOCOM*, 2003.

[2] C. Barrett, D. Beckman, M. Khan, V. A. Kumar, M. Marathe, P. Stretz, T. Dutta, and B. Lewis. Generation and analysis of large synthetic social contact networks. In *Winter Simulation Conference*, 2009.

[3] C. Barrett, R. Beckman, K. Channakeshava, F. Huang, V. S. A. Kumar, A. Marathe, M. Marathe, and G. Pei. Cascading failures in multiple infrastructures: From transportation to communication network. In *5th International conference on Critical Infrastructures (CRIS)*, 2010.

[4] C. L. Barrett, R. J. Beckman, K. P. Berkbigler, K. R. Bisset, B. W. Bush, K. Campbell, S. Eubank, K. M. Henson, J. M. Hurford, D. A. Kubicek, M. V. Marathe, P. R. Romero, J. P. Smith, L. L. Smith, P. L. Speckman, P. E. Stretz, G. L. Thayer, E. V. Eeckhout, and M. D. Williams. Transims: Transportation analysis simulation system. *Technical Report LA-UR-00-1725, Los Alamos National Laboratory*, 1997.

[5] R. Beckman, K. Channakeshava, F. Huang, V. A. Kumar, A. Marathe, M. Marathe, and G. Pei. Implications of dynamic spectrum access on the efficiency of primary wireless market. *IEEE Dynamic Spectrum Access Networks, DySPAN*, April 2010.

[6] R. Beckman, K. Channakeshava, F. Huang, V. A. Kumar, A. Marathe, M. Marathe, and G. Pei. Synthesis and analysis of spatio-temporal spectrum demand patterns: A first principles approach. *IEEE Dynamic Spectrum Access Networks, DySPAN*, April 2010.

[7] T. Camp, J. Boleng, and V. Davies. A survey of mobility models for ad hoc network research. *Wireless Communications and Mobile Computing (WCMC): Special issue on Mobile Ad Hoc Networking: Research, Trends and Applications*, page 483502, 2002.

[8] L. Li, D. Alderson, W. Willinger, and J. Doyle. A first principles approach to understanding the internets router level topology. In *ACM SIGCOMM*, 2004.