their attack in advance, criminals opportunistically react to real-time information in the network.

The second contribution is a game-theoretic approach to generate randomized patrol schedules. We model the interactions between criminals and the police as a Stackelberg game, with the police acting as the leader and criminals as followers. However there are two differences with previous work in Stackelberg Security games. First, criminals react to real-time information in our model as mentioned earlier, which is different from previous work. Second, after one attack, criminals can still stay in the network and find another target to attack using our QBRM model, which is modeled as crime diffusion. Our objective is to find a randomized patrol strategy for the police that optimizes her expected utility against crime diffusion. We formulate the problem as a nonlinear optimization problem on a Markov chain model.

2. RELATED WORK

There has been research on a wide range of topics related to controlling diffusion in networks. One line of work considers game-theoretic models of controlling contagion in networks. These are games between defenders and attackers where the attacker attempts to maximize its diffusion influence over the network while the defender tries to minimize this influence. Algorithms have been proposed to approximately solve such games under different models of diffusion, including [14] for the Independent Cascade Model (ICM) and [9] for the Linear Threshold Model (LTM). In these contagion games, the two players can only select a number of initial seed nodes and their influence diffuses automatically. Such models are thus not applicable to model the opportunistic criminals.

Another line of research uses recent advances in criminology on opportunistic criminal behavior to describe crime diffusion in networks. [11] applied a biased random walk model for house burglary, and [15] analyzed the effect of the police on controlling the crime diffusion in the house burglary domain. In their works, criminals have no knowledge of the overall strategy of the police, and their behavior is only affected by their observation of the current police allocation in their immediate neighborhood. Also in [15], police behave in a similarly reactionary way, allocating their resources in an instantaneously optimal way in response to the current crime risk distribution rather than optimizing over the time horizon and within a transportation network.

The motions of both criminals and police in [15] also vary significantly from those in the current work. Each instance of a criminal's motion in [15] may only be between adjacent locations, after which the nearby police allocation is observed anew and another movement can be made, leading to highly localized diffusion of criminals. In contrast, criminals in the current work may make "large" directed movements over the transportation network between distant locations, as they see fit, before updating their beliefs and moving again, leading to much less localized crime. Furthermore, in [15] there is no notion of the "movement" of police - rather, the distribution of police is chosen to be instantaneously optimal, with no regard for the mechanics of exactly how the allocation may transform from one timestep to the next.

Game theoretic approaches have been successfully applied to security domains for generating randomized patrol strategies against strategic adversaries, e.g., [13] generated schedules for the Federal Air Marshals to protect flights; [10] generated schedules for the US Coast Guard to protect ports; and [4] generated schedules for Los Angeles Sheriff Department to conduct fare checking on the LA Metro network.

Our approach combines and generalizes the randomized patrolling model of previous security applications and the criminology-based random-walk diffusion model of [11]: now police can move inside the network in a randomized fashion, and the criminals are opportunistic and can diffuse throughout the network.

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4. REFERENCES

[1] P Jeffrey Brantingham and George Tita. Offender mobility and crime pattern formation from first principles. *Artificial crime analysis systems*, 2008.

[2] Patricia Brantingham and Paul Brantingham. Criminality of place. *European Journal on Criminal Policy and Research*, 3(3):5–26, 1995.

[3] Marcus Felson and Ronald Victor Gemuseus Clarke. *Opportunity makes the thief: Practical theory for crime prevention*, volume 98. Home Office, Policing and Reducing Crime Unit, Research, Development and Statistics Directorate, 1998.

[4] Albert Xin Jiang, Zhengyu Yin, Chao Zhang, Milind Tambe, and Sarit Kraus. Game-theoretic randomization for security patrolling with dynamic execution uncertainty. In *AAMAS*, 2013.

[5] Kees Keizer, Siegwart Lindenberg, and Linda Steg. The spreading of disorder. *Science*, 322(5908):1681–1685, 2008.

[6] Anastasia Loukaitou-Sideris. Hot spots of bus stop crime: The importance of environmental attributes. *JAPA*, 65(4):395–411, 1999.

[7] Anastasia Loukaitou-Sideris, Robin Liggett, and Hiroyuki Iseki. The geography of transit crime documentation and evaluation of crime incidence on and around the green line stations in los angeles. *JPER*, 2002.

[8] Stephen A Matthews, Tse-Chuan Yang, Karen L Hayslett, and R Barry Ruback. Built environment and property crime in seattle, 1998–2000: A bayesian analysis. *Environment and planning. A*, 42(6):1403, 2010.

[9] Thanh H Nguyen, Jason Tsai, Albert Jiang, Emma Bowring, Rajiv Maheswaran, and Milind Tambe. Security games on social networks. In *AAAI Fall Symposium Series*, 2012.

[10] Eric Shieh, Bo An, Rong Yang, Milind Tambe, Craig Baldwin, Joseph DiRenzo, Ben Maule, and Garrett Meyer. Protect: A deployed game theoretic system to protect the ports of the united states. In *AAMAS*, 2012.

[11] Martin B Short, Maria R D'Orsogna, Virginia B Pasour, George E Tita, Paul J Brantingham, Andrea L Bertozzi, and Lincoln B Chayes. A statistical model of criminal behavior. *Mathematical Models and Methods in Applied Sciences*, 18(supp01):1249–1267, 2008.

[12] Ralph B Taylor and Adele Harrell. *Physical environment and crime*. US Department of Justice, Office of Justice Programs, National Institute of Justice, 1996.

[13] Jason Tsai, Christopher Kiekintveld, Fernando Ordonez, Milind Tambe, and Shyamsunder Rathi. Iris-a tool for strategic security allocation in transportation networks. In *AAMAS Industry Track*, 2009.

[14] Jason Tsai, Thanh H Nguyen, and Milind Tambe. Security games for controlling contagion. In *AAAI*, 2012.

[15] Joseph R Zipkin, Martin B Short, and Andrea L Bertozzi. Cops on the dots in a mathematical model of urban crime and police response. 2013.