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Spatio-Temporal Competition for Transportation Resources

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***Abstract*—A lot of work has been devoted to collaboration among distributed computing devices. Sensor networks and crowdsourcing are prominent examples of distributed collaborative computing. Much less attention has been paid to competition among computing agents, particularly the type that we call spatio-temporal competition. In it mobile agents compete for point resources located in space. An example of such competition is drivers, guided by their smartphones, attempting to park; they are competing for a limited number of parking spaces. This is an example, but spatio-temporal competition arises in many other transportation applications. Furthermore, it gives rise to new research problems which will be described in this presentation.**

***Keywords*-mobile computing, game theory, equilibrium, optimum, pricing, stable-marriage**

I will briefly describe the IGERT interdisciplinary PhD program in Computational Transportation Science at the University of Illinois at Chicago. The program lies at the intersection of Computer Science and Transportation. The description will include several Intelligent Transportation applications and research projects in the program. They involve spatio-temporal data management on vehicles and smart-phones, as well as communication among them. The applications' objectives are to improve safety, mobility, convenience, efficiency, and environmental impact of urban transportation.

Then I will focus on the problem of spatio-temporal competition for resources. It consists of n mobile agents (e.g. vehicles) competing for m static resources (e.g. parking slots, or taxi cab customers) in the plane or the road network. A resource can be used by a single agent at a time, and thus the competition among the agents for the resources. A solution to the problem is a 1-to-1 matching between agents and resources. We consider mainly travel time as the optimization criterion, i.e. we assume we are interested in a matching that minimizes the total travel-time. However, we will also discuss the extension to other criteria such as $-cost. We also assume that each agent wants to minimize her travel time to capture a resource.

This dichotomy between the social welfare (minimizing total travel-time) and selfishness (minimizing individual travel time) gives rise to a gap. This is a gap between the optimal and the Nash equilibrium matching of resources and agents. We will show that the algorithms for the two types of matching, although both efficient, are totally different. Then we will show that in the worst case the ratio between the two (often called the Price of Anarchy) is unbounded, but in practice it is usually not higher than 30%. We also discuss the commonality and differences between the problem of Spatio-temporal competition and the Stable Marriage (see [1]) problem.

Then we will discuss an incomplete-information variant of the problem, where each agent knows the locations of the resources, but not the locations of the other competing agents. This situation arises in an experimental project in San Francisco called SFPark (see http://sfpark.org/). The project uses sensors buried in the pavement to detect when street-parking slots are occupied and released. The results are posted on a web site in the form of a street-block parking availability map. Drivers then consult this map to determine where to park. Of course, this raises safety concerns due to the fact that drivers looking to park frequently glance at their smart-phone. Thus, it is desirable that an app guides the driver to the most appropriate parking slot, similarly to the way a car-navigation-system guides her to her destination. This app would be aware of the available parking-slot locations, but not the locations of the other vehicles searching for parking, thus the practical motivation for the incomplete information variant of Spatio-temporal competition.

We propose a gravitational approach to the incomplete-information problem, in which resources exert a gravitational force on the mobile agents. In turn, each agent moves according to the vector-sum of the forces exerted on it by the resources. We show that the Gravitational approach is more efficient by up to 40% than the Greedy, or nave, approach in which each agent simply pursues the closest resource. The implications of this comparison are compelling. Studies conducted in 11 major cities reveal that the average time to search for curbside parking is 8.1 minutes and cruising for these parking spaces accounts for 30% of the traffic congestion in those cities on average (see [2]). Even if the average time to find parking were smaller, it would still account for a large amount of traffic. Suppose that the average time to find parking were 3 minutes, each parking space would still generate 1,825 vehicle miles traveled (VMT) per year ([3]). That number would of course be multiplied by the number of parking spaces in the city. For example, in a city like Chicago with over 35,000 curbside parking spots ([4]), the total number of VMT becomes 63

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million VMT per year due to cruising while searching for parking. Furthermore, this would account for a waste of over 3.1 million gallons of gasoline and over 48,000 tons of CO2 emissions. Therefore, even a 10% reduction in the time to find parking would have important ramifications for urban transportation and the environment.

Next we discuss congestion pricing strategies to mitigate the gap between the optimum and equilibrium solutions to the Spatio-temporal Competition problem. The motivation is that social welfare favors the optimum, but agents selfishness forces the system into an equilibrium state. By pricing the resources we can convert the equilibrium to the optimum. In other words, the equilibrium when considering both travel-time and price (assuming some standard conversion between travel-time and $-cost) is the optimum when considering travel-time alone. In routing this conversion from equilibrium to optimum is achieved by tolling. In other words, tolls on certain road-segments can convert the equilibrium to a minimum total travel time, i.e. social welfare. We adapt an existing (Auction) algorithm for this type of pricing. However, the Auction pricing algorithm does not provide guarantees for individual agents in terms of the total price.

Therefore, we discuss an additional pricing scheme in which each agent is guaranteed to pay a price (including travel-time and $-cost) that is not higher than her price in equilibrium. The agent may travel longer than in equilibrium, but in this case she will be compensated by a $-reward. If she travels shorter than in equilibrium, then she will pay a $-price. We provide the guarantee by $-price-discrimination, i.e., different agents may pay different $-prices for the same resource. An important result from the practical point of view is that the Agent-guarantee pricing scheme is self-sustaining, i.e. does not need to be subsidized. In other words, the total $-price that agents pay is not higher than the total $-price that agents are being paid.

Time permitting, I will discuss additional aspects of the Spatio-temporal competition, namely: truthfulness, i.e. incentivizing agents to disclose their true travel-times to the resources; management of uncertainty; and detection of spatial resources by time-series analysis of smart-phone sensor data.

This talk is based in part on references [5], [6], [7].

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