WHITE PAPER

Collaborative Data Transmission and Quality of Routing Games for Resilient Wireless Networks

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Wireless networks such as sensor networks and more general adhoc networks are essential components of a trusted future system architecture that will provide safeguards to prevent or lessen the frequency of the occurrence of disasters and mitigate their catastrophic impact, as well as rapid and effective responses to disasters (natural or man-afflicted) immediately after they occur. Such networks consist of distributed arrays of sensors that can collect, store, and disseminate a variety of environmental information and data. To make these networks resilient in the face of failures, along with effective and seamless communication, we need to develop appropriate link and routing layer data transfer mechanisms that provide minimum quality of service guarantees. In this white paper, we propose two techniques for reliable communication and forwarding in wireless networks: collaborative relaying and quality of routing based congestion games.

1 Quality of Routing Congestion Games

Motivation: Game-theoretic models have been extensively used to model traffic flows in networks. Routing games based on node/link congestion reflect energy consumption and hence network lifetimes. Thus it is meaningful to formulate and evaluate games of traffic flow in heterogenous sensor networks. Given the increasing presence of heterogeneity in sensor networks (for example, sensor networks in SCADA systems), it makes sense to consider the availability of different traffic routing classes in the network analogous to the idea of Quality of Service classes in wired networks. A particular routing class may be composed of nodes with a specific range of available energies. A given routing class can thus guarantee minimal connection lifetimes based on the number of nodes participating in that class. A node can pay a given service cost to participate in routes belonging to a particular traffic class. Each class guarantees a minimum routing quality. However if too many nodes select a particular class, the quality of routing will obviously deteriorate. We can assume that nodes in a particular routing form a separate subnetwork and only route traffic flows in the class. Thus nodes in different classes do not affect energy consumptions and hence congestion in each other.

We are thus motivated to develop routing games based on the availability of different traffic routing classes. We characterize each routing class by a fixed service cost which reflects the connection/energy guarantees provided by the class. A class with high service costs may correspond to a subnetwork of nodes with high available energies. Since these nodes can transmit at higher powers, they can guarantee lower delays and higher successful transmission probabilities. However nodes with higher service costs may be attractive for these reasons and thus have higher congestion which degrades performance. Hence the metric which reflects overall costs to participants in a routing class is the sum of a fixed service cost and variable congestion costs.

Approach: We consider network congestion games where there is a set of N players and each player has to select a path from a source node to a destination node in the network. We consider *atomic* congestion games where the flow of each player is unsplittable, that is, all the traffic flow of the player is sent along one path from the source to the destination. The paths selected by different players may interfere with each other when they have common edges. We use as a path interference metric the *edge congestion*, where the congestion of an edge is the number of player paths that use the edge. Each selected path has a cost which is related to the congestion of its bottleneck edge (the most congested edge along the path). The players select paths that minimize the costs, that is, they prefer paths with lower congestion. Edge congestion is an appropriate cost metric which relates to the energy required to transmit packet along that edge, that is, the higher the congestion on an edge the more the energy needed to transmit the packets. Thus, lower congestion implies increased lifetime for the network. Further congestion is related to the scheduling time for sending the packets, the higher the congestion, the faster the packet delivery schedule.

We can develop *quality of routing congestion games (QoR games)*, where the paths are partitioned into m routing classes $Q_1, \ldots, Q_m$, where each routing class Q_j has a service cost $S(Q_j)$. Each path in the network (and hence the path selected by a player) is assigned to exactly one of those routing classes. The paths in different routing classes do not affect each other, that is, any two paths in different routing classes do not cause congestion to each other. This non-interfering property can be achieved by selecting the paths of different classes to be edge-disjoint, or by assigning the paths of each routing class to a different transmission channel (e.g. with frequency or time-division multiplexing). Thus, only players within the same routing class can cause congestion to each other (analogous to packets on the same frequency channel causing congestion to each other in a frequency multiplexed routing scheme).

For a player i the cost function is defined as $C_i + S_i$, where S_i is the service cost of the routing class that the path of i belong s to, and C_i is the congestion of the bottleneck edge of the player's chosen path, where the congestion is measured only among the paths that belong to the same routing class as player i.

We can show [1] that QoR games always have pure Nash equilibria, which can be obtained with best response dynamics, where each player greedily improves its path whenever possible. QoR games may possibly have multiple Nash equilibria. We quantify the effect of selfishness with the *price of stability* and *price of anarchy*, which express how much larger is the social cost in a Nash equilibrium compared to the social cost in the optimal coordinated solution. Price of stability (PoS) is the ratio of the best Nash equilibrium social cost to the optimal social cost. Price of anarchy (PoA) is the ratio of the worst Nash equilibrium social cost to the optimal social cost. We have examined *restricted-QoR* games where the service cost of each class is at least the length of each path that the class contains. Such games are interesting when different routing classes correspond to different ranges of path lengths; for example, it could be more costly to use longer paths than shorter paths. We showed that the price of anarchy in any restricted-QoR game is bounded as:

$$PoA = O(\min(C^*, S^*) \cdot m \log n),$$

where n is the number of nodes in the underlying graph. Therefore, when either of C^* or S^* is small (e.g. a constant), and the number of classes m is small, the Nash equilibrium provides a very good approximation to the coordinated routing problem. Thus, in those scenarios the effect of selfishness is small, which is an important result that shows that the local optimality and selfishness can provide good outcomes for the global social welfare.

2 Collaborative Data Transmission for Resilient and Secure Wireless Sensor Networks

Motivation: Sensor networks are essential components of a trusted future system architecture that will provide both safeguards to prevent or lessen the frequency of the occurrence of disasters and/or to mitigate their catastrophic impact as well as rapid and effective responses to disasters (natural or man-afflicted) immediately after they occur. Catastrophic events, such as hurricanes, lead to a rapid and often dramatic deterioration in the performance of communication and sensor networks. These networks are the primary means of communication between first responders and impacted citizens and any performance degradation can severely impact the type and quality of emergency response provided to survivors. There are four primary network conditions that lead to performance degradation during times of systemic stress: *1) System Overload:* Initial spikes in network usage result in an initial decline in throughput, which in turn leads to rapidly increasing loads and eventually dramatically lower performance. This was seen in the cellular network during hurricane Katrina with lost calls leading to ever increasing loads, eventually disabling the cellular network; *2) Sensornet Channel Quality:* Severe weather also impacts communication channel quality; attenuation in uplink/downlink channels impacts base station-mobile communication while increased cross-channel interference due to higher activity impacts adhoc network performance; *3) Sensornet Spectrum Availability:* While the FCC mandates the availability of wireless communication spectrum for primary users such as established sensornets, secondary users with cognitive/software defined radios can scavenge unused bands. Without proper spectrum allocation algorithms, there can be competition among secondaries and less-efficient utilization of available spectrum; *4) Security and Energy Efficiency:* Most network devices have limited and unreplenishable energy stores and thus security protocols and sensing schedules must be designed with energy conservation and lifetime maximization in mind.

Approach: Collaborative data transmission in wireless sensor networks has garnered significant recent interest due to the potential for improved link-layer reliability, connectivity and throughput at higher energy efficiencies. Relaying via appropriately chosen intermediate nodes exploits cooperative diversity, which provides an additional diversity path through the relay which may be significantly better than the direct source-destination path. Consider a simple network of three nodes: the source node, the destination (cluster head or sink node) and a relay node (an adjacent wireless node). If the relay is able to receive and decode/amplify the source's message, even if there are errors on the direct link, the combined mutual information can minimize the outage probability (packet loss probability) and information will be correctly received at the destination. Thus relaying can improve reliability and other performance metrics through diversity gain.

There are several important and fundamental issues regarding how relaying and partnership construction can improve wireless network functionality during disaster events. For example, we must 1) examine the impact of acquiring Channel State Information (CSI) on developing adaptive signaling schemes and constructing relay partnerships, 2) evaluate the efficiency of Orthogonal vs. Non-Orthogonal Channel Allocation i.e. Time/Frequency Division Multiple Access (TDMA/OFDM) based communication versus interference channel based communication and 3) address energy tradeoffs made by relay nodes between transmitting their own data and forwarding the other nodes information. Channel quality can be used as one possible metric while evaluating these tradeoffs.

During emergent situations (such as hurricanes or strong weather events) gathering CSI from wireless nodes might be inefficient due to time delays. At other times, using CSI can lead to improved relaying efficiencies through exploiting cooperative diversity. Thus we must attempt to develop solutions to relaying problems under the whole spectrum of CSI availability: ranging from full CSI to no-CSI including such aspects as finite rate feedback (i.e bandwidth limited feedback from nodes to basestation) Both centralized and distributed scheduling and power control algorithms must be examined. We should also investigate relaying when nodes are orthogonally transmitting i.e Time/Frequency Division Multiple Access (TDMA/OFDM) and also under simultaneous transmission by multiple nodes over interference channels. Given the possible selfish nature of relaying due to limited power budgets, we need to develop comprehensive models for analyzing relaying in wireless networks under realistic networking constraints such as finite rate feedback, interference and self-interest.

References

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