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Network Coding and QoS Routing for Wireless Networks

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1 Aim and Objectives

With the rapid development of wireless technology, smart wireless environment become the evolutionary step in building, industrial, home and transportation etc. Real-time applications such as high quality video broadcasting are expected for wireless ad hoc networks in near future. But the unpredictable nature of the wireless environment is easily prone to failures and resulting path failures and data loss. Thus the Quality of Service of routing technique in wireless networks becomes a hot topic and it is the first focus in our current research.

In our previous research, we focused on the reliability and survivability aspects of routing protocols in large networks. Our approach is to find multiple disjoint paths between a pair of nodes with different bandwidth requirements, we have also studied the unsplittable flow problem and the Inner-node Weighted Minimum Spanning Tree Problem, which are also very useful for building high-speed network infrastructures. However, all these methods were started from an algorithmic aspect, with no consideration from the information theory view that may break the limits of discrete algorithm design.

We are interested in combining information theory into problem models, with which the performance of the algorithms can be evaluated better. For example, signal interference is a very important factor that affects the simultaneous availability of links in wireless networks. Recently, network coding has emerged as a technique with the potential to make communication over networks both more efficient and more robust. Here we will focus on the rate control problem for network coding in unicast networks at first. This problem is different from the multicast case, especially when users have non-shared resources that can be used either for their own dedicated transmissions, or for transmitting the redundant information necessary for network coding.

Secondly, research of network coding in wireless networks is still in its infancy. We expect that variations of modern coding methods like Turbo coding, LDPC coding and its associated iterative decoding algorithms will provide the tools to construct useful network coding strategies for wireless networks. So we will try to search and develop practical network coding strategies for future wireless systems, with emphasis on channel modelling and wireless network analysis and optimization.

Finally, we will try to bring game theory into the study of wireless ad-hoc networks. We believe that insights from modelling an ad-hoc network as a competitive market would be useful in designing practical, distributed resource allocation mechanisms with minimal overhead and desirable QoS properties.

2 Idea and Approach

Survivable network operation requires networks to be able to detect failures when they occur, and then to reroute traffic over alternate paths. Two objectives, which are usually contradictory, are the requirements to recover from failures expeditiously, and to minimize the resources reserved by the network to recover from those failures. We will use network coding to achieve both objectives. With the use of network coding, different sessions combine their signals on shared protection circuits, hence reducing the amount of required resources, while always providing receivers with backup copies of transmitted signals, therefore allowing instantaneous data recovery. We will develop network coding-based protection strategies for single link failures, and will then extend the strategies to protect against multiple link failures. Implementation strategies in different protocols, such as IP and MPLS, will also be developed, and additional router and switch functionalities to implement the proposed protection techniques will be introduced. Hybrid strategies, combining different types of protection techniques, including network coding, 1:N and M:N protection, will also be investigated as a means of further reducing the amounts of required resources, while guaranteeing an upper bound on the data recovery time.

On the other hand, our research will be based on modelling wireless information flows and constructing a theoretical framework for network coding in wireless networks. As an extension of routing in multi-hop networks, our research incentives incorporate the principle of network coding (that allows intermediate relay nodes to perform distributed coding over the received signals) in wireless communication. We will work on novel graph-theoretic models with new information-theoretic implications to describe the wireless information flows in ad hoc and sensor networks. A distributed network coding approach will be developed in conjunction with scheduling-based medium access control for throughput and energy-efficient network operation. The benefits of network coding will also be evaluated in stable operation with random access. The primary goals of distributed implementation, decentralized control and self-organization will be pursued to apply network coding in wireless network scenarios with continuously changing topology, packet traffic and channel conditions due to the mobility effects and limited energy resources. This line of research invokes the need for a new formulation of network information flows, since the classical models of information theory and graph theory cannot effectively represent wireless communication properties of interference effects among activated links, omnidirectional transmissions and single transceiver per node.

For the topic in game theory, we shall focus on cooperative communication while taking into account the fact that users will cooperate for the purpose of maximizing their utility, while in the mean time forming a cooperative group will yield a complexity penalty on the cooperating transmitters. Hence, we will study the trade off between cooperative gains and complexity penalties that is the design of cooperative strategies that maximize the gains as long as the cost for cooperation is not high. In this sense, we will aim at devising strategies for users' cooperation within wireless networks based on game theory concepts such as coalitions and repeated games. In fact, a solution for the problem of transmitter cooperation can be found through using a special form of coalition games known as partition function form as it provides an interesting mathematical tool to model cooperative games whereby the utility depends on the coalition structure that is formed in the whole network. Thus, we will do an exhaustive review and investigate the possibility of using this special form for modelling the transmitter cooperation problem. Additionally, the cooperation among the transmitters will be inspected at various levels (transmit power, spreading codes, etc.) for the purpose of deriving a suitable algorithm that will allow transmitter cooperation and the formation of stable transmitter coalition structures.

3 The Progress In the Past Year

- We have implemented the collision avoidance algorithm on the OMNET++ simulation platform. Then combine all the algorithms designed and propose a fault-tolerant collision-free routing framework for large networks.
- We have designed design improved Approximation Algorithms for the Minimum-cost Single-Source Unsplittable Flow Problem, the metric version of facility location problems and MSTI problem, and used MatLab to test their performance.
- We have proposed a new framework for scalable topology control in wireless sensor networks; this framework is used in a object racking system. Currently we are building emulation test bed for it.
- We have found some construct examples for two users for the unicast case where first using non-shared resources for dedicated transmissions and then network coding over any leftover resources is a dominant strategy that achieves the network capacity. In such examples, the rate control problem can be modelled as a multipath routing problem where the paths available to each user can be categorized as one of three types: paths for dedicated transmissions over non-shared resources, paths for multicast network coding, and traditional routing paths over "leftover" shared resources. We used the insights gained from such examples in developing distributed rate control schemes for multipath routing in unicast networks that employ network coding.
- From the perspective of non-cooperative games, we have looked at basic wireless network problems of random access, power and rate control in single destination systems, and joint medium access control and routing/network coding in multi-hop operation over relay channels. We have also developed cooperation incentive mechanisms (e.g. for packet forwarding) with distributed implementation for reliable and efficient network operation.

4 Future directions

- We will work on extending the traditional information-theoretic tools to embrace practical issues in mobile wireless networks with emphasis on stability with finite delay, protocol information, finite memory and transient operation with finite energy.
- We will further try evaluating the wireless channel capacity results through the application of practical multi-user detectors with different throughput and energy properties for network coding in wireless networks.
- From the perspective of multi-user information theory, we will separately study the effects of directional antennas on the asymptotic capacity and scalability of the stable throughput in general wireless networks.

- The problem of utility optimization in wireless networks cannot be decomposed into layers without loss of optimality. We will apply game-theoretic tools to look at trade-offs between layering for optimization decomposition and cross-layer design for performance efficiency.

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