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Coordination and resilience in wireless adhoc and sensor networks

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Summary

In wireless adhoc and sensor networks a close synergy and coordination is required among entities at different layers of the network architecture to achieve the robust behavior that is expected from these systems in the potentially harsh environments where they may operate. The volatile wireless channel, the unpredictability of traffic due to unknown traffic generation scenarios as well as variability of the network topology itself due to mobility and node failures set a challenging stage for the network designer. A mathematical network model that captures the interaction of mechanisms at the different layers, from physical to transport as well as the intricacies of the time varying network topology was considered in [1,2,3] and refined and generalized later in several other papers. A brief description of that model is as follows. All the physical and access layer parameters including power selection, channel allocation, coding rate etc are collectively represented through a vector $I(t)$. The relevant parameters of the environment that affect the communications as well as the topology of the network itself are represented collectively by the topology state variable $S(t)$.The topology state might not be fully available to the access controller, who may observe only a sufficient statistic of that. The collection of bit rates of all the communicating pairs of nodes at each time, i.e. the communication topology, is represented by a function $C(I(t), S(t))$ where $I(t)$ is selected by the physical/access layer controller. Over the virtual communication topology the traffic flows from the origin to the destination according to the network and transport layer protocols. Packets may be generated at any network node having as final destination any other network node potentially several hops away. The network control mechanism determines the access control vector and the traffic forwarding decisions in order to accomplish certain objectives. An important performance attribute is the capacity region of the network defined as the set of all end-to-end traffic load matrices that can be supported under the appropriate selection of the network control policy. That region is characterized in two stages. First the ensemble of all feasible long term average communication topologies is characterized. The capacity region includes all traffic load matrices such that there is a communication topology from the ensemble for which there is a flow that can carry the traffic load and be feasible for the particular communication topology. An

approach to characterize the performance of a control policy for the network is by the policy capacity region, i.e. the collection of traffic load matrices that are sustainable by the specific policy. The larger the capacity region is the better the performance will be since the network will be stable for a wide range of traffic loads and therefore more robust to traffic fluctuations. Such a performance criterion makes even more sense in the context of wireless ad-hoc and sensor networks where both the traffic load as well as the network capacity may vary unpredictably; in that case robustness is a valuable attribute. That perspective to the control of the network was introduced in [1]. A control policy was proposed there that achieves the objective in an optimal manner optimally since it has a capacity region that coincides with the capacity region of the network and is therefore a superset of the capacity region of every other policy. The selection of the various control parameters from the physical to transport layer is done in two stages in that policy. In one stage all the parameters that affect the transmission rates of the various wireless links are selected while on the other the assignment of the traffic classes to the different connections is done. Its description though is facilitated by starting with the traffic forwarding part first. Each traffic class is routed such that the backlog of the class is balanced across the network at each time. The traffic of class k backlogged at node i is forwarded to downstream nodes with smaller backlogs, towards equalizing the load while the flow is throttled towards downstream nodes with higher backlogs for the same reason. The link capacity is allocated to the different traffic classes waiting for transmission through the link to the benefit of the traffic class with most unevenly distributed backlog. More specifically, through the link from node i to node j the traffic class with larger difference between the backlogs at i minus that of j is given priority for transmission. Based on the above considerations a weight w_{ij} is determined for link (i, j), indicating how much the backlog distribution will be uniformized by the transmission through the link (i, j). If the link capacity is fixed and independent of allocation decisions in neighboring links, as is the case in wireline networks, the above resource allocation rules are adequate for traffic control to stability. That is not the case though for a wireless network where the link capacity is determined by the access control vector selection $I(t)$. Effectively a bandwidth allocation decision to the different links is done that way and the bit rates $C(I(t), S(t))$ are specified at t. This is done such that the links with higher backlog weight w_{ij} are favored in their neighborhood and they are given a higher rate C_{ij} through the selection of the physical and access layer parameters. More specifically $I(t)$ is selected such that the sum of the resulting bit rates C_{ij} weighted by the corresponding weights w_{ij} is maximized. Since the bit rate of the link usually depends on the access parameters in a complicated way while the links interact due to interference, the optimization for different links may need to be performed jointly. As a result the access optimization problem might be both computationally hard and it may require centralized coordination. Several subsequent works focused on dealing with the challenges posed by implementable distributed versions of the policy. In various occasions a wireless network might be operating in overload conditions, i.e.

outside of its stability region as defined above. A smooth and balanced system response in those stressful situations is essential for effective crisis management in the network. That problem is studied in [4]. A network consisting of an arbitrary spatial arrangement of nodes is considered where information may be generated at any node in the network and needs to be forwarded to a collection of hub (sink) nodes. When the traffic load lies outside the feasibility region of the system, there is no feasible flow to transfer the information to the sinks, given the capacity of the system. In that case traffic backlogs will occur in the nodes. The distribution of the backlog build-up is an indication of the behavior of the system. A fluid model is considered in [4] where the information flow induced by the routing policy is represented by superflows. A superflow is a generalized notion of flow, where the aggregate incoming flow in a node may exceed the outgoing. The difference of incoming minus the outgoing flow from a node is the backlog buildup rate at the node. That difference is called "node overload". The vector of node overloads under a certain routing policy is the quantitative performance objective that represents the overload response of the network to the routing policy. It is shown in [4] that in the space of node overload vectors there is one that is lexicographically minimal and is characterized. The overload corresponding to this vector also maximizes the information rate that reaches the sinks. Furthermore it is shown that this vector is the unique solution for a wide class of optimization problems where the optimization objective function is the sum of any non-decreasing convex function of node overloads. That vector is called "most balanced" overload vector and any superflow that induces the most balanced overload vector, "most balanced" superflow. A distributed adaptive superflow reallocation policy converging to a most balanced superflow is presented finally. That initial work sets the framework for studying the overload behavior of other wireless adhoc network architectures as well, towards more resilient wireless networks.

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[2] L. Tassiulas and A. Ephremides, "Dynamic server allocation to parallel queues with randomly varying connectivity," IEEE Transactions on Information Theory, vol. 39, no. 2, pp. 466–478, 1993.

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[4] L. Georgiadis and L. Tassiulas, "Most balanced overload response in sensor networks," in IEEE International Symposium on Information Theory, Adelaide, Australia, September 2005.