Design and analysis of a novel Opportunistic Routing protocol for congestion control in WSN

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Abstract: Traditional routing strategies for multi-hop wireless networks forward packets by selecting at the sender side the next hop for each packet. The problem of routing packets across a multi-hop network consisting of multiple sources of traffic and wireless links while ensuring bounded expected delay. Each packet transmission can be overheard by a random subset of receiver nodes among which the next relay is selected opportunistically. The main challenge in the design of minimum delay routing policies is balancing the trade-off between routing the packets along the shortest paths to the destination and distributing traffic according to the maximum backpressure. Combining important aspects of shortest path and backpressure routing, this paper provides a systematic development of a distributed opportunistic routing policy with congestion diversity (D-ORCD). D-ORCD uses a measure of draining time to opportunistically identify and route packets along the paths with an expected low overall congestion. D-ORCD is proved to ensure a bounded expected delay for all networks and under any admissible traffic. Furthermore, this paper proposes a practical implementation which empirically optimizes critical algorithm parameters and their effects on delay as well as protocol overhead. And demonstrate a significant networks improvement in the average delay over comparative solutions.

***Index Terms* - Congestion measure, implementation, Lyapunov analysis, opportunistic routing, queuing stability, wireless ad hoc networks.**

I. INTRODUCTION

Wireless networks typically use routing techniques similar to those in wired networks [15, 16, 9, 4, 5]. These traditional routing protocols choose the best sequence of nodes between the source and destination, And forward each packet through that sequence. Opportunistic routing for multi-hop wireless ad-hoc networks has long been proposed to overcome deficiencies of conventional routing [1]-[5]. Opportunistic routing mitigates the impact of poor wireless links by exploiting the broadcast nature of wireless transmissions and path diversity.

More precisely, the routing decisions are made in an online manner by choosing the next relay based on the actual transmission outcomes as well as a rank ordering of neighboring nodes. The authors in [4] provided a Markov decision theoretic formulation for opportunistic routing and a unified framework for many versions of opportunistic routing [1]–[3], with the variations due to the authors' choices of costs. In particular, it is shown that for any packet, the optimal routing decision, in the sense of minimum cost or hop-count, is to select the next relay node based on an index. This index is equal to the expected cost or hop-count of relaying the packet along the least costly or the shortest feasible path to the destination.

When multiple streams of packets are to traverse the network, however, it might be necessary to route some packets along longer or more costly paths, if these paths eventually lead to links that are less congested. More precisely, and as noted in [6], [7], the opportunistic routing schemes in [1]–[5] can potentially cause severe congestion and unbounded delays (see examples given in [6]). In contrast, it is known that an opportunistic variant of backpressure [8], diversity backpressure routing (DIVBAR) [7] ensures bounded expected total backlog for all stabilizable arrival rates. To ensure throughput Optimality (bounded expected total Backlog for the all Stabilizable arrival rates), backpressure-based algorithms [7], [8] do something very different from [1]–[5]: rather than using any metric of closeness (or cost) to the destination, they choose the receiver With the largest positive differential backlog (routing responsibility is retained by the transmitter if no such receiver exists). This very property of ignoring the cost to the destination, however, becomes the bane of this approach, leading to poor delay performance in low to moderate traffic (see [6]). Other existing provably throughput optimal routing policies [9]–[12] distribute the traffic locally in a manner similar to DIVBAR and, hence, result in large delay. Recognizing the shortcomings of the two approaches, researchers have begun to propose solutions which combine elements of shortest path and backpressure computations [7], [15],

In [7], E-DIVBAR is proposed: when choosing the next relay among the set of potential forwarders, E-DIVBAR considers the sum of the differential backlog and the expected hop-count to the destination (also known as ETX). However, E-DIVBAR does not necessarily result in a better delay performance than DIVBAR. Instead of a simple addition used in EDIVBAR, this paper provides a distributed opportunistic routing policy with congestion diversity (D-ORCD) under which the congestion information is integrated with the distributed shortest path computations of [4]. In our previous work [13], ORCD, a centralized version of D-ORCD, is shown to be throughput optimal without discussion on system implications. In this paper, we extend the throughput optimality proof for the distributed version and discuss implementation issues in detail. We also tackle some of the system level issues. Then show that D-ORCD exhibits better delay performance than state of the art routing policies, namely, EXOR, DIVBAR and E-DIVBAR. Before we close, we emphasize that some of the ideas behind the design of D-ORCD have also been used as guiding principles in many routing solutions: some in opportunistic context [14], [15] and some in conventional context [16]. We detail the similarity and differences between these solutions and our work for the sake of completeness, even though, in our study, we have chosen to focus only on solutions with comparable overhead and similar degree of practicality. In [14], perhaps the most related work to ours, the authors Consider a flow-level model of the network and propose a routing policy referred to as min-backlogged-path routing, under which the flows are routed along the paths with minimum total backlog. In this light, D-

ORCD can be viewed as a packet-based version of the min- backlogged-path routing without a need for the enumeration of paths across the network and costly computations of total backlog along paths. In [15], authors propose a modified version of backpressure which uses the shortest path information to minimize the average number of hops per packet delivery, while keeping the queues stable. In [16], a modified throughput optimal backpressure policy, LIFO- Backpressure, is proposed using LIFO discipline at layer 2. Neither of these approaches lends themselves to practical implementations: [15] requires maintaining large number of virtual queues at each node increasing implementation complexity, while [16] uses atypical LIFO scheduler resulting in significant reordering of packets. Furthermore, while LIFO Backpressure policy guarantees stability with minimal queue length variations, realistic bursty traffic in large multi-hop wireless networks may result in queue-length variations and unnecessarily high delay.

II. RELATED WORK

The number of nodes in a network is too large, then the expected number of a batch's packets that any given node is responsible for forwarding might be close to zero. In that case ExOR's agreement and scheduling protocols will have high overhead, since they have costs proportional to the number of nodes. For this reason the ExOR source includes only a sub-set of the nodes in the forwarder list. The source runs an ExOR simulation based on the link loss probabilities and selects only the nodes which transmit at least 10% of the total transmissions in a batch. The source chooses the forwarder list using network-wide knowledge of inter-node loss rates. The source can acquire this knowledge via periodic link-state coding of per-node measurements. ExOR is relatively insensitive to inaccurate or out-of-date measurements, since a packet's actual path is determined by conditions at the time of transmission. Incorrect measurements may degrade performance by causing the forwarder list order to be incorrect, or by causing nodes to be inappropriately included or excluded from the list.

III. ROUTING CONGESTION DIVERSITY

The previous analysis, we can establish a first upper bound on the packet propagation speed, when a classical routing strategy is employed, i.e., when packets are forwarded in “push mode” to the next relay on a hop by hop basis. For the analysis, we consider that the distribution of the signal to noise ratio is exactly known and that classical routing is optimized to achieve the fastest propagation speed under this distribution. We describe the guiding principle and the design of Opportunistic Routing with Congestion Diversity (D-ORCD). We propose a time-varying distance vector, which enables the network to route packets through a neighbor with the least estimated delivery time. D-ORCD opportunistically routes a packet using three stages of: (a) transmission, (b) acknowledgment, and (c) relaying. During the transmission stage, a node transmits a packet. During the acknowledgment stage, each node that has successfully received the transmitted packet sends an acknowledgment (ACK) to the transmitter node. D-ORCD then takes routing decisions based on a congestion-aware distance vector metric, referred to as the congestion measure. More specifically, during the relaying stage, the relaying responsibility of the packet is shifted to a node with the least congestion measure among the ones that have received the packet. The congestion measure of a node associated with a given destination provides an estimate of the best possible draining time of a packet arriving at that node until it reaches destination. Each node is responsible to update its congestion measure and transmit this information to its neighbors. Next, we detail D-ORCD design and the computations performed at each node to update the congestion measure.

Congestion Computations

The congestion measure associated with node i for a destination d at time t is the aggregate sum of the local draining time at node i (denoted by Ldi (t)) and the draining time from its next hop to the destination (denoted by Dd i (t)), i.e. Assuming a FIFO discipline at layer-2, we proceed to decompose the local draining time. This relies on the

Observation that when a packet arrives at a node, i, its waiting time is equal to the time spent in draining the packets that have arrived earlier plus its own transmission time. If P(I;d)(t) denotes the probability that the packet transmitted by node i is successfully received by a node with lower congestion measure, then expected transmission time at node i for the packet is given by 1 Pi;d(t) .

$$V_i^d(t) \quad = \quad L_i^d(t) + D_i^d(t).$$

Let Qdi(t) denote the number of packets destined for destination d averaged over previous computation cycle. Qdi(t) is updated as D-ORCD computes the expected congestion measure “down the stream” for each node i to using the latest congestion. The three-way handshake procedure discussed in Section II-A to achieve receiver diversity gain in an opportunistic scheme is achieved at the cost of an increase in the control overhead. In particular, it is easy to see that this overhead cost, which is the total number of ACKs sent per data packet transmission, increases linearly with the size of the set of potential forwarders. Thus, we consider a modification of D-ORCD in the form of opportunistically routing with partial diversity (P-ORCD). This class of routing policies is parameterized by parameter M denoting the maximum number of forwarder nodes. This is equivalent to a constraint on the maximum number of nodes allowed to send acknowledgment per data packet transmission. Such a constraint will sacrifice the diversity gain, and hence the performance of any opportunistic routing policy, for lower communication overhead.

IV. PERFORMANCE EVOLUTION

We compare the expected delay encountered by the packets in the network under various opportunistic routing policies: ExOR, DIVBAR, E-DIVBAR and D-ORCD. We first investigate the performance of D-ORCD with respect to a canonical example to demonstrate D-ORCD gains [6]. We then use a realistic topology of 16 nodes placed in a grid.

Topology to demonstrate the robust performance improvement in practical settings. A. We consider two set of topologies in our experimental study:

1) Canonical Example: In this example, we study the canonical example in Fig. 4. We motivate the performance improvement for D-ORCD by a scenario which exemplifies the need to avoid congestion in the network by highlighting the shortcomings of the existing routing paradigms: shortest path and backpressure. 2) Grid Topology: We study outdoor wireless settings of grid topology consisting of 16 nodes separated by a distance of 200 meters. These simulations demonstrate a robust performance gain under D-ORCD in a realistic network. We now describe the parameters settings in the simulation.

$$Q_i^d(t) = \frac{T_s}{T_c}\sum_{l=0}^{\frac{T_c}{T_s}-1} Q_i^d(T(t)-l).$$

$$L_i^d(t) = \frac{1}{P^{(i,d)}(t)} + \sum_{d'\in\Omega} \frac{Q_i^{d'}(T(t))}{P^{(i,d')}(t)}.$$

The nodes are equipped with 802.11b radios transmitting at 11 Mbps with transmission power 15 dBm. The wireless medium model includes Rician fading with K-factor of 4 and Lognormal shadowing with mean 4dB. In the canonical example path loss is determined by path loss matrix which gives the attenuation of the received signal power with distance from the transmitter for every pair of network nodes, while for grid topology the path loss follows ITM model in [21]. The antenna model is the standard omnidirectional antenna model with the default settings of the simulator. The network queues are FIFO with finite buffer of 750 KB. The acknowledgement packets are short packets of length 24 bytes transmitted at 11 Mbps, while FO packets are of length 20 bytes and transmitted at lower rate of 1Mbps to ensure reliability. If unspecified, packets are generated according to position modulated Markov traffic. The packets are assumed to be of length 512 bytes equipped with simple cyclic redundancy check (CRC) error detection. The control packets are transmitted periodically at an interval of Ts = 0:5 seconds.

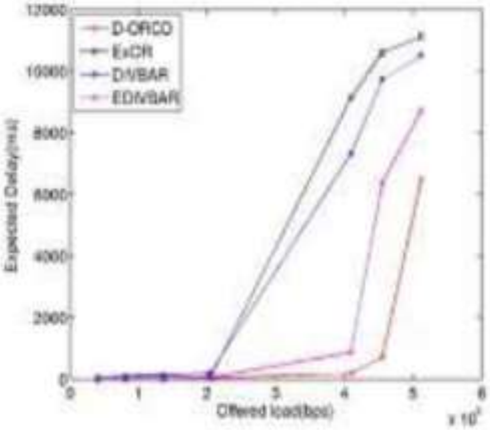

Fig1. Performances shown to be the centralization of the routing/scheduling globally across the network or a constant factor performance loss of the distributed variants [7], [10], [25]. In future, we are interested in generalizing DORCD for joint routing and scheduling optimizations as well consider system level implications.

V. CONCLUSION

The integrated routing and MAC protocol for multi-hop wireless networks in which the \best" of multiple receivers forwards each packet. In this paper, combining the important aspects of shortest path routing with those of backpressure routing, we provided a distributed opportunistic routing policy with congestion diversity (D-ORCD) is proposed under which packets are routed according to a rank ordering of the nodes based on a congestion cost measure. Furthermore, we show that DORCD allows for a practical distributed and asynchronous 802.11 compatible implementation, DORCD consistently outperforms existing routing algorithms in practical settings. In D-ORCD, we do not model the interference from the nodes in the network, but instead leave that issue to a classical MAC operation. However, the generalization to the networks with inter-channel interference follows directly from [7]. The price of this generalization is shown to be the centralization of the routing/scheduling globally across the network or a constant factor performance loss of the distributed variants.

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