Achieving Cesaro-Wardrop equilibrium in Wireless Sensor Networks

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***Abstract*— We consider a wireless sensor network in which the sensor nodes are sources of delay insensitive traffic that needs to be transferred in a multi-hop fashion to a common processing center. We address the problem of optimal routing that aims at minimizing the end-to-end delays. Since we allow for traffic splitting at source nodes, we propose an algorithm that seeks the Wardrop equilibrium instead of a single least delay path. The algorithm is implemented in TinyOS.**

I. Introduction

We propose an adaptive and distributed routing scheme for a general class of wireless sensor networks. The objective of our scheme is to achieve Cesaro Wardrop equilibrium [3], an extension of the notion of Wardrop equilibria that first appeared in [1] in the context of transportation networks. The notion is defined in Equation (1) later in this paper.

We let ϕ denote the $n\times n$ routing matrix. The $(i,j)^{th}$element of this matrix, denoted $\phi_{i,j}$, takes value in the interval $[0,1]$. This means a probabilistic flow splitting as in the model of [2], i.e., a fraction $\phi_{i,j}$ of the traffic *transmitted* from node i is forwarded by node j. Clearly, we need that ϕ is a stochastic matrix, i.e., its row elements sum to unity. We assume that the system operates in discrete time, so that the time is divided into (conceptually) fixed length slots.

Under the above model there will be a delay, say $y_{j,i}$ of the packet from node j to be served at node i; this packet could have originated at node j or may have been forwarded by node j. The Expected delay of a packet transmitted from node j is thus $\sum_{i\neq j}\phi_{j,i}y_{j,i}$. Since delays are additive over a path, packets from any node will have a delay over any possible route to the fusion center. A route will be denoted by an ordered set of nodes that occur on that route, i.e., the first element will be the source of the route, the last element will be the fusion center and the intermediate elements will be nodes arranged in the order that a packet traverses on this route. Let the total number of possible routes (cycle-free) be R. Let route i, $1\leq i\leq R$ be denoted by the set $\mathcal{R}_i$ consisting of R_i elements with $\mathcal{R}_{i,j}$ denoting the j^{th}entry of this route. Then, a traffic splitting matrix will correspond to a Wardrop equilibrium iff for any i (see [1] for this definition)

$$\sum_{1\leq j\leq R:\mathcal{R}_{j,1}=i}\left(\prod_{k=1}^{R_j-1}\phi\mathcal{R}_{j,k},\mathcal{R}_{j,k+1}\right) \left(\sum_{k=1}^{R_j-1}y\mathcal{R}_{j,k},\mathcal{R}_{j,k+1}\right)=\sum_{k=1}^{R_l-1}y\mathcal{R}_{l,k}\mathcal{R}_{l,k+1}, \quad (1)$$

for any l with $\mathcal{R}_{l,1}=i$ and such that $\prod_{k=1}^{R_l-1}\phi\mathcal{R}_{l,k},\mathcal{R}_{l,k+1}>0$, i.e., the delays on the routes that are actually used by packets from node i are all equal. Our objective in this paper is to come up with an algorithm using which any node (say i) is able to converge to the corresponding row of the matrix ϕ corresponding to the Wardrop equilibrium.

II. Distributed Routing Algorithm

Let $\phi(n)$ denote the traffic splitting matrix at the beginning of the n^{th} time slot. Node i does some computation to update the i^{th} row of this matrix. Let $Y^k(n)(\mathcal{R}_{k,1}=i)$ be the new value of the delay of a packet sent by sensor i through route $k(i=\mathcal{R}_{k,1})$. Node i keeps an estimate of the average delay on route k.

$$y^k(n+1)=(1-a)y^k(n)+aY^k(n). \quad (2)$$

Further, after calculating the expected delays at the start of a time slot, each node adapts its routing probabilities ϕ to the new expected delays. For the convergence of our routing algorithm in practice, we need to ensure that the probabilities $\phi_{i,j}$ are strictly positive for all feasible routes to ensure that we are able to probe for a change in the state of all the available routes. Note that this convergence is for the average of delays, this is what we mean by Cesaro-Wardrop equilibrium. We have implemented the routing algorithm as a part of multihop routing layer protocol in TinyOS.

III. Conclusions and Future Work

For wireless sensor networks with random channel access, we proposed a learning algorithm, applicable to a general class of WSNs, to achieve Wardrop equilibrium for the end-to-end delays incurred on different routes from sensor nodes to the fusion center. We are now working on modifications of the algorithm to make it converge to an *efficient* equilibrium.

References

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