

Report for EE590 : A Study of Dynamic Routing and Power Control in Time Varying Wireless Networks

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1 Introduction

The communication channels in a wireless network (e.g. cellular networks, mobile ad hoc networks or sensor networks) are inherently time varying. This can be due to a variety of reasons including user mobility, wireless fading, environmental conditions etc. This feature of the underlying channel affects the decisions of power allocation, scheduling and routing, fundamental to the network's operation. To maximize the performance of the network, it is necessary to take this feature into account while making the above decisions.

In this report, we study the dynamic control schemes proposed in [1], [2] that use backlog and channel state information to make joint decisions about routing and power control in time varying wireless networks. In section 2, we consider a simple "multiple source - single sink" sensor network where the channel states vary every time slot according to a Bernoulli process. Using simulations, we compare the performance of the DRPC scheme proposed in [1] with a fixed shortest path routing scheme on this simple topology. We argue that backlog and channel aware schemes perform much better than static shortest path based schemes. Further, performance of DRPC can be improved at low data rates by taking into account path lengths while calculating backpressure. We then consider a more general scenario where transmitting nodes can cause interference at other nodes.

In [2], an energy optimal control strategy EEPC is proposed for time varying wireless networks. This scheme also uses backlog and channel state information to make routing and power control decisions. The scheme is shown to approach the minimum power at the cost of a linear increase in average delay. In section 3, we propose a modification to EEPC that results in a sublinear increase in delay. We analyze the performance of this modified scheme using a cubic Lyapunov function and simulate the modified scheme on a simple cell partitioned sensor network topology.

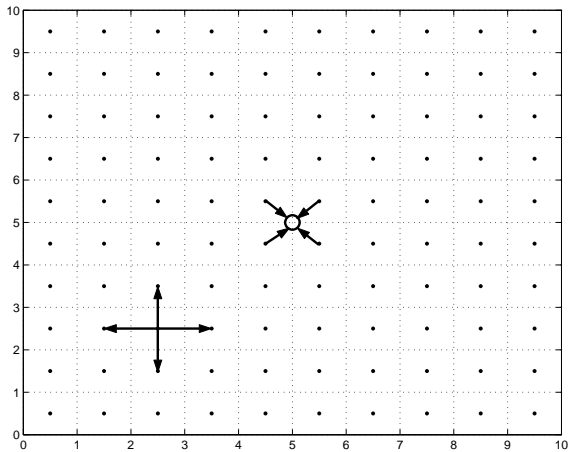


Figure 1: A simple multiple source single sink topology

2 A Comparison between DRPC and Shortest Path Routing

In this section, we compare DRPC/EDRPC with a static shortest path based routing scheme. We use a simple cell partitioned network of multiple sources and single sink. The simulation results show that backlog and channel state aware schemes perform much better than static schemes.

2.1 Simulation Model

We consider a simple “multiple source single sink” static sensor network of 100 nodes as shown in figure 1. The nodes are assumed to form a cell partitioned structure with one node in each cell. Each node can communicate with neighboring nodes on its North, South, East and West. We assume that each node can transmit to at most one of its neighbors at a time, though a node can receive from multiple nodes. This is possible if neighboring nodes use orthogonal frequency bands. We further assume that a node’s transmission doesn’t cause interference at other nodes.

The sink is located at the center of the network (shown as a circle in figure 1) and has four neighbors. Each node generates data according to a Poisson process with rate λ and this is routed to the sink over multiple hops.

We assume that the channel states of each link vary according to an ON/OFF process every time slot independently. Both states are equally likely. A node can transmit over a link only when the channel state for that link is ON. Furthermore, nodes are assumed to have a fixed transmission power P_{MAX} . The data rate achievable over a link is then taken as $BW \log(1 + \alpha P_{MAX})$ where α is the attenuation over that link, being 0 for OFF state and 1 for ON state and BW is the bandwidth of the link.

In this setup, it can be seen that the nodes that are immediate neighbors of the sink form the

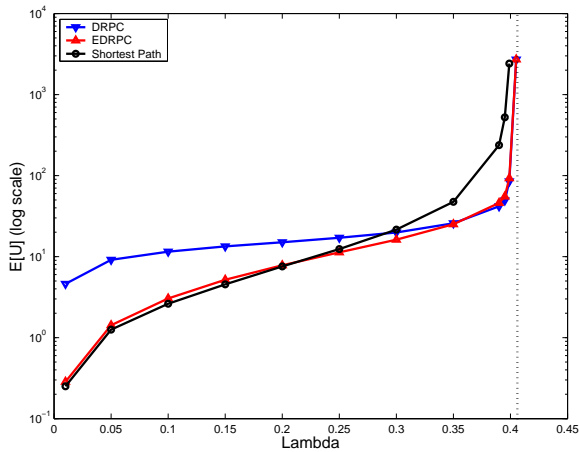


Figure 2: Average Queue Occupancies for DRPC, EDRPC and Shortest Path Routing for same bottleneck link capacities

bottleneck for the network throughput. This is because these nodes have to carry all the traffic generated by all the nodes in the network. Specifically, if all nodes transmit at an average rate λ , then for network stability, we require $\lambda \leq \frac{BW_{total} \log(1+P_{MAX})}{100 \times P_{ON}}$ where BW_{total} is the total bandwidth available to the bottleneck nodes.

2.2 Simulation Results

We simulated the DRPC and EDRPC schemes on the setup described above. In the first simulation, all the bottleneck links have same bandwidth. Fig 2 compares the performance (in terms of average queue occupancies) of DRPC and EDRPC with a static shortest path based scheme where a node always forwards data to its parent node in the shortest path tree rooted at the sink for this setup. It is seen that while DRPC outperforms shortest path routing at high data rates, all schemes achieve the capacity. At low data rates, backlog based decisions are likely to lead to false turns, which degrades the performance of DRPC. By incorporating path lengths into the backpressure calculation, EDRPC improves upon the performance of DRPC at low data rates while maintaining the advantages of backlog aware schemes at high data rates.

Next we consider the scenario where the bandwidths of two of the bottleneck nodes are doubled. Now the capacity region has increased and while DRPC/EDRPC achieve it, shortest path based scheme is unable to do so (see fig 3).

Finally we consider a similar multiple source single sink network, but now a node's transmission causes interference at other nodes. In this scenario, the optimization problem of DRPC (see [1]) becomes nonlinear, non-convex and difficult to solve. We therefore use an approximation based approach

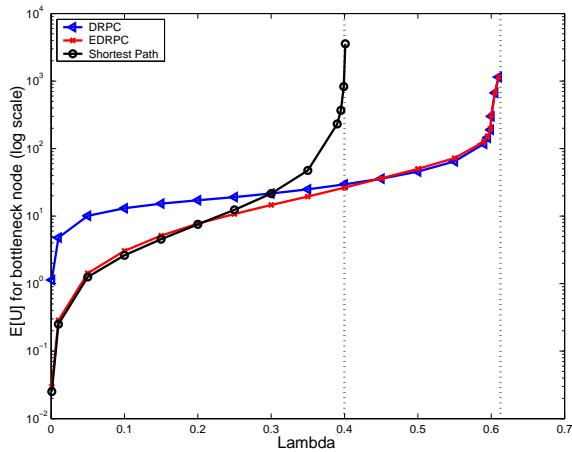


Figure 3: Average Queue Occupancies for DRPC, EDRPC and Shortest Path Routing for different bottleneck link capacities

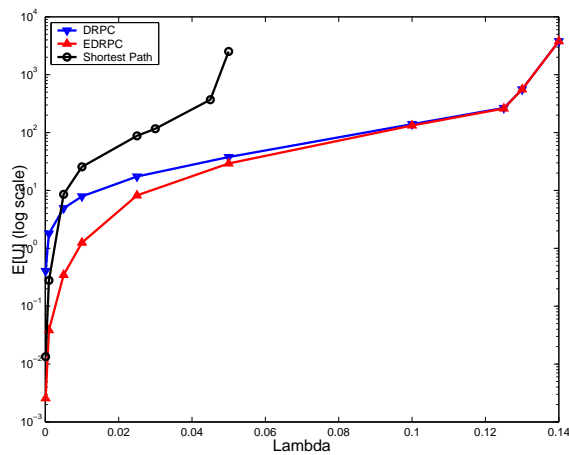


Figure 4: Average Queue Occupancies for DRPC, EDRPC and Shortest Path Routing when nodes cause interference

where each node randomly decides to transmit at full power at the beginning of each slot with probability $1/2$. We now simulate the DRPC/EDRPC and shortest path based scheme on this network and fig 4 compares their performance. It is seen that the backlog aware schemes perform much better than shortest path routing. In fact, DRPC/EDRPC are seen to support much higher data rates than shortest path routing.

3 A Modified Energy Efficient Power Control Scheme

In this section we present a modified Energy Efficient Power Control scheme (EEPC, see [2]) that offers performance gains over EEPC in terms of average delay. The modified scheme for a single hop network can be summarized as follows.

Every timeslot, observe the current queue backlog $\vec{U}(t)$ and channel state $\vec{S}(t)$ and allocate a power vector $\vec{P}(t) = (P_1, \dots, P_L)$ according to the following optimization:

$$\text{Maximize: } \sum_l [3U_l^2(t)\mu_l(P_l, S_l(t)) - VP_l]$$

$$\text{Subject to: } \vec{P}(t) = (P_1, \dots, P_L) \in \Pi$$

where Π is a compact set of acceptable power vectors

In order to obtain performance bounds for the modified scheme, we use a cubic Lyapunov function.

We present the analysis for a single hop network having L links in the next section.

3.1 Analysis using Cubic Lyapunov function for Single Hop Networks

Let $A_l(t)$ represent the of number of new bits arriving at link l at the beginning of slot t . Let the L -dimensional power allocation and channel state vectors be $\vec{P}_l(t)$ and $\vec{S}_l(t)$. The dynamics of unfinished work $\vec{U}_l(t)$ of the network can be expressed as follows:

$$\vec{U}(t+1) \leq \max [\vec{U}(t) - \vec{\mu}(\vec{P}(t), \vec{S}(t)), 0] + \vec{A}(t) \quad (1)$$

Now we define a Lyapunov function $L(\vec{U}(t)) = \sum_l [U_l(t)]^3$. Taking cubes of both sides of the dynamics equation, we get at a link l :

$$U_l^3(t+1) - U_l^3(t) \leq -3U_l^2(t)\delta_l + 3U_l(t)\delta_l^2 + (K_l - \beta_l^3 + A_l^3 + 3A_l\beta_l^2)$$

where

$$\delta_l = \mu_l(P_l(t), S_l(t)) - A_l(t)$$

$$\beta_l = \mu_l(P_l(t), S_l(t))$$

$$K_l = \min ([U_l(t) - \beta_l]^3) \text{ for } U_l(t) \geq 0$$

Since $U_l(t) \geq 0$, it can be shown that $K_l = -\beta_l^3$. Summing over all links, we have:

$$\sum_l (U_l^3(t+1) - U_l^3(t)) \leq -3 \sum_l U_l^2(\mu_l - A_l) + 3 \sum_l U_l(\mu_l - A_l)^2 + \sum_l (K_l - \beta_l^3 + A_l^3 + 3A_l\beta_l^2) \quad (2)$$

Taking conditional expectation:

$$\Delta(\vec{U}(t)) = E[L(\vec{U}(t+1)) - L(\vec{U}(t)) | \vec{U}(t)]$$

$$\leq -3 \sum_l U_l^2 E((\mu_l - A_l) | \vec{U}(t)) + 3 \sum_l U_l E((\mu_l - A_l)^2 | \vec{U}(t)) + CL$$

$$\leq -3 \sum_l U_l^2 [E(\mu_l | \vec{U}(t)) - \lambda_l] + 3 \sum_l U_l^2 [(E(\mu_l | \vec{U}(t)) - \lambda_l)^2 + \sigma_l^2] + CL$$

where

$$C = A_{max}^3 - 2\beta_{max}^3 + 3A_{max}\beta_{max}^2$$

$$\sigma_l^2 = E[(\mu_l - A_l)]^2 - (E[\mu_l - \lambda_l])^2$$

Now using a procedure similar to the one used in [2], we add and subtract the term $V \sum_l E[P_l(t) | \vec{U}(t)]$

and by a simple manipulation, obtain the following

$$\begin{aligned} \Delta(\vec{U}(t)) \leq & \\ & CL - V \sum_l E[P_l(t)|\vec{U}(t)] + 3 \sum_l U_l^2 \lambda_l + 3 \sum_l U_l^2 [(E(\mu_l|\vec{U}(t)) - \lambda_l)^2 + \sigma_l^2] \\ & - E \left(\sum_l [3U_l^2(t)\mu_l(P_l(t), S_l(t)) - VP_l(t)]|\vec{U}(t) \right) \end{aligned}$$

By maximizing the last term in the above expression over all possible power allocation strategies, the cubic Lyapunov drift for the modified EEPC scheme can be expressed in terms of the drift of the stationary randomized power allocation strategy that chooses power independent of queue backlog.

We get

$$\Delta(\vec{U}(t)) \leq CL - V \sum_l E[P_l(t)|\vec{U}(t)] + 3 \sum_l U_l^2 \lambda_l + 3 \sum_l U_l^2 (\epsilon') - \left(\sum_l [3U_l^2(t)(\lambda_l + \epsilon) - VP_{av}(\epsilon)] \right)$$

where

$$E[(\mu_l|\vec{U}(t)) - \lambda_l]^2 + \sigma_l^2 \leq \epsilon' (\forall l)$$

Taking expectations over the distribution of $\vec{U}(t)$ gives:

$$\begin{aligned} & E \left\{ L(\vec{U}(t+1)) - L(\vec{U}(t)) \right\} \\ & \leq CL - 3(\epsilon - \epsilon') \sum_l E(U_l^2) + VP_{av}(\epsilon) - V \sum_l E(P_l(t)) \end{aligned}$$

Thus, using lemma 1 from [2] the time average unfinished work satisfies:

$$E \left\{ \sum_l U_l \right\} \leq \sqrt{E \left\{ \left(\sum_l U_l \right)^2 \right\}} \leq \sqrt{\frac{CL^2 + VLP_{av}(\epsilon)}{3(\epsilon - \epsilon')}}$$

and time average power satisfies:

$$E \left\{ \sum_l P_l \right\} \leq P_{av}(\epsilon) + CL/V$$

3.2 Simulation Results

We compare the performance of the EEPC scheme with the modified EEPC scheme using the same multiple source single sink sensor network model described earlier. We choose data rates λ such that they lie in the capacity region on the network. Fig 5 a shows the average queue lengths for EEPC and modified EEPC schemes for different values of the control parameter V . It can be seen that the average queue lengths for modified scheme grow slower than EEPC with increasing values of V .

Fig 6 shows the average power spent for EEPC and modified EEPC schemes for different values of V . The average power approaches the minimum power with increasing values of V for both the schemes, though more quickly for EEPC.

Fig 7 compares average delay and power for both the schemes. While the modified scheme shows some improvement in average delay over a range of average power values, it essentially increases similar to the original scheme as the average power goes to the optimal value. This raises interesting questions related to fundamental energy-delay tradeoffs in wireless networks. Specifically, is the energy-delay tradeoff for the original scheme the best one could do? We would like to investigate this issue in the

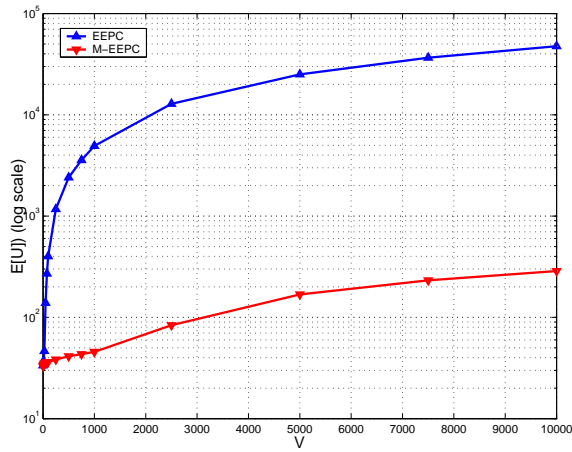


Figure 5: Average queue length for EEPC and modified EEPC scheme

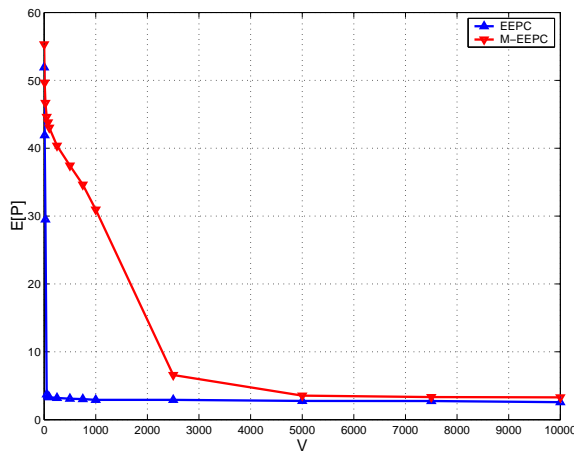


Figure 6: Average power spent in EEPC and modified EEPC scheme

future.

4 Conclusions and Future Work

In this study, we showed using simulations that backlog and channel state aware schemes like DRPC/EDRPC are an attractive choice for wireless networks as these scheme achieve network capacity and outperform traditional shortest path based schemes. We plan to demonstrate this on real experimental test beds as part of future work.

References

- [1] M. J. Neely, E. Modiano, and C. E. Rohrs, “Dynamic Power Allocation and Routing for Time Varying Wireless Networks,” To appear in IEEE Journal on Selected Areas in Communications,

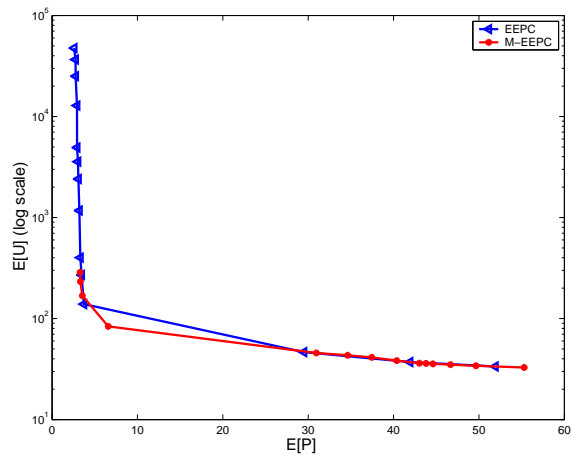


Figure 7: Average Queue Occupancies for DRPC, EDRPC and Shortest Path Routing

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- [2] M. Neely, "Energy Optimal Control over Time Varying Wireless Networks," under submission
- [3] M. J. Neely and E. Modiano, "Improving Delay in Ad-Hoc Mobile Networks Via Redundant Packet Transfers," Proceedings of the Conference on Information Sciences and Systems, Johns Hopkins University March 2003