Answer all parts of all questions. There are four multi-part questions, each of equal weight. Turn in your answers by Thursday, December 11, at the same time you picked up your exam, to Jennifer Streubel at MCS-140G.

Brevity is the soul of wit. Be brief and to the point. This is a depth exam. So, your answers should show research maturity and depth. Do not pad your answers and do not write for the sake of writing.

You are free to consult any notes, books and papers during the examination, but make sure to include your references. You must develop your own solutions, which might use existing ideas and techniques, as long as you cite them and clearly explain how these existing ideas/techniques fit within your own solution.

You are not allowed to consult with any person during the examination.

If you have any doubt as to the interpretation of a question, make a reasonable assumption and explain your interpretation in your answer. No explanations will be given during the exam.
1. Using virtual circuit switching technology (such as ATM, MPLS, WDM), the provider of a service charges a price for each physical link on the network. Typically, the price of a link depends on the reserved capacity, with a lower bit-per-second pricing for larger reserved capacities. In such a setting, a customer $i$ would specify a source $s_i$, a destination $d_i$, and the amount of flow traffic $f_i$ it needs to transport. The provider would create a virtual circuit, charging customer $i$ a price based on the reserved bandwidth on each physical link in the (shortest) path between $s_i$ and $d_i$.

In an attempt to reduce their costs, a group of (rational, selfish) customers decided to take matters in their own hands by creating a shared overlay network over which they would route their traffic. For now, you should not worry about how this overlay was created. There is an incentive for customers to do this because if they buy bulk capacity from the underlay they get much lower costs. In this setting each customer is free to choose an overlay path for its flow traffic. Since the benefit to a customer from sharing underlying physical links depends on the aggregate level of traffic carried by the physical link, it follows that one customer’s choice of an overlay path will change the utility of another customer, introducing a game in which customers take turns in choosing overlay paths that maximize their utilities. We call this the “Path Collocation Game” (PCG).

Assume that there are no restrictions on capacity of any physical link, i.e., customers can ask and pay for as much capacity as they want on any given physical link. Also, assume that the pricing function is sublinear, i.e., the larger the reserved capacity, the cheaper the price per bandwidth unit.

Consider a setting in which all customers have unit traffic flows. Let the utility of using an overlay link by customer $i$ be the summation of the traffic flows of all other customers using that link, and let the utility of an overlay path be the summation of the utilities of all the links in that path.

(a) What sensible reasons can you give for choosing the specific form of the utility function as described above?

(b) Under the above setting, show that a potential function exists, and hence PCG convergence to an equilibrium is guaranteed.

Under the above setting, although PCG’s outcome may be an equilibrium, it may not necessarily be optimal in terms of the average (or aggregate) utility for all customers.

(c) Give at least one example of a sub-optimal equilibrium.

(d) Can you provide a bound on the price of anarchy? If your answer is yes, then provide a bound, otherwise show that it can be arbitrarily large.

The above setting is a bit artificial since the utility function does not correspond directly to the real cost to a customer, and since it assumes that all traffic flows are of equal weight and that physical links are not capacitated. Coming up with more realistic utility functions that guarantee convergence to an equilibrium is an open question, and you are to push the envelop in order to make the setting under which convergence is guaranteed as realistic as possible.

(e) Reformulate the utility function so that it would be more realistic by relaxing some of the assumptions made in the above setting? For example you may consider a setting in which the customer pays a fraction of the cost of the link (in proportion to its use by the customer), or you may assume that the capacity of the underlay links is limited.

(f) For your formulation, can you prove that the game will converge to an equilibrium? If not, can you show that it may not converge (by giving a a counter example)?

As stated, the topology of the overlay network (i.e., how the customers are connected to each other) is given and is assumed to be fixed while the game is played.

(g) Discuss approaches you may consider for setting up the overlay, providing pros and/or cons for each. Also, discuss the practical implications/complications from using a dynamic overlay.

You are now convinced that this is an interesting problem worth writing a paper on.
(h) Write a one-page motivation for a paper on this problem. In particular, you must explain why a game setting is warranted, as opposed to viewing this problem as a central optimization problem. Also, you should convince the reader that the network provider has no incentive to help the customers, hence the need for a distributed implementation of a customer’s best response.

(i) Write a one-page related work section for a paper on this problem. What areas of networking research deserve mention? and what are the key papers in each?

(j) Could PCG be implemented in practice? What information would each customer need in order to compute locally its best response? Can PCG be played in a fully distributed fashion? Explain.
2. Consider a wireless company whose product is a caching proxy that could be deployed in UMTS networks to improve throughput and delay performance of applications. A basic UMTS network consists of a number of the following components: UE (User Equipment), BS (Base Station), RNC (Radio Network Controller), SGSN (Serving GPRS Support Node), and GGSN (Gateway GPRS Support Node). Figure 1 shows a typical UMTS hierarchical network configuration with two possible locations for the caching proxy at the RNC or GGSN. The BS employs per-user queues that are scheduled according to some channel-dependent proportionally fair scheduling (PFS) algorithm. Under PFS, users with better wireless channels are given priority and transmission rates are modulated to ensure almost zero transmission errors. For the purpose of this question, you can think of other UMTS nodes (RNC, SGSN, GGSN) as routers, where GGSN also acts as the interface between the UMTS network and the rest of the Internet.

![Figure 1: UMTS setup](image)

You are asked to evaluate the deployment of such caching proxy for TCP-based applications, e.g., FTP or web (as shown in figure). There are two basic goals. The first goal is to improve performance by placing one caching proxy somewhere within the UMTS network—at the BS, RNC, SGSN or GGSN. The second goal is to dimension the UMTS links appropriately—specifically, if the cache hit rate is reasonably high, the bandwidth of some of the UMTS links could be reduced, thus their bandwidth cost may be reduced to the point of even offsetting some (or all) of the cost of buying the caching proxy.

(a) Develop a simple analytical model that captures cache performance, load on links, and TCP performance, for the downlink traffic from Internet nodes to UEs. Your model may abstract the whole hierarchical network by a single path, for example, by introducing appropriate models of cross traffic on different links. You should start simple, for example, by assuming a single main TCP-based traffic source, a simple TTL-based caching algorithm at a given UMTS node (BS, RNC, SGSN, or GGSN), a simple round-robin behavior for the scheduler at the BS (assuming same wireless channel conditions across UEs), zero transmission errors over the wireless links, and a steady-state AIMD TCP behavior.

(b) Develop an optimization formulation whose objective function depends on the throughput or delay performance of applications, as well as the bandwidth allocated on (cost of) the UMTS links.

(c) Given reasonable values for the input parameters (bandwidth, propagation delays, packet losses of links, web object sizes, packet sizes, etc.), solve your optimization model to demonstrate optimal cache placement and UMTS link dimensioning. Assume that the maximum per-user download bandwidth from the BS scheduler over the wireless link is 8Mbps, and the maximum upload bandwidth is 384 Kbps. You should consider cases where the bottleneck is at either side of the caching proxy. Compare with the base case where no caching proxy is deployed. You should make your solution (e.g., MATLAB or C/C++/Java code, plots, documentation) available online and provide a URL to it.

(d) Suggest extensions to your analytical model that would allow for more detailed analysis. Also discuss ways to validate your analysis using simulations or live experiments—make sure you describe the setup of your testbed and what aspects of your analysis you will be validating.
3. This question is based on the paper “Robust dynamic classes revealed by measuring the response function of a social system,” http://arxiv.org/pdf/0803.2189v1.

You should start by reading the paper carefully.

(a) There are four classes of dynamics described in the paper. Assume you are going to design a classifier that distinguishes the four classes in an online manner. Assume that you have access to a real-time feed of the number of requests for a given video.

i. Describe the design of a classifier that distinguishes, given the stream of requests, which of the four classes the request stream falls into.

ii. Describe the design of a detector that identifies the presence/absence and location of the peak in the stream sequence. Discuss the issues involved and why you made the choice you did.

iii. You will probably use some sort of signal processing technique(s) to build your classifier and detector. Describe what alternatives you considered, and the reasons you chose the technique(s) you did.

(b) One assumption in the paper is made in adopting equation (1) to describe user behavior. Assume you are the operator of a social networking and video website, like YouTube. How could you verify whether equation (1) is a good assumption? Be as specific as you can.

(c) Assume your classifier and detector operate well. Also assume that you are the operator of a content delivery system, so you have control over and can change the configuration and/or operation of both the network, the content servers, and any other equipment you choose to include in the system. In the context of such a content delivery system, what use could you make of your classifier/detector tool to improve system performance or operation? Be as specific as you can.

(a) Darryl Veitch provided a public review for this paper, also at the link above. Provide your own 1-2 page public review, making sure to comment on the value (or lack of value) in the problems considered, in the heuristics developed, and in the experimental results. Since your review is not actually going to be made public, you should feel free to discuss limitations of the work and provide a more critical assessment than the Veitch review, if you see fit. A good public review draws in an outside perspective without directly rehashing ideas already provided in the paper.

(b) In Section 3.3, the authors briefly mention (one sentence) the following idea. “The substrate router can use consistent hashing to minimize the fraction of flows that must change paths when the splitting ratio changes or new paths are created.” Elaborate this idea, sketching out how consistent hashing would be applied here and stating the benefits of the method in this context. Separately, argue for or against this methodology.

(c) Two central ideas in the paper are to allow the network to split virtual links into multiple substrate paths and to migrate a virtual link from one set of paths to an alternate set of paths. The authors caution that the substrate network may not always be able to support these two options; moreover, there may be virtual networks which are unsplittable and non-migrateable. For each of these four possibilities, either provide a convincing scenario where the problem arises, or argue that the problem arises rarely, if ever.