Computational Mechanism Design for Allocating Tactical Network Bandwidth

IN A NUTSHELL

Problem

Centralized resource allocation becomes problematic as systems grow in scale and complexity. A centralized decision maker must know what is needed at any time by all the parts of a system, including its "user parts." At some point, the diversity and number of tasks that a system must perform makes this kind of omniscience impossible. If omniscience can't be achieved, a centralized decision maker must rely on the system parts to truthfully report their needs. However, assuming that a system's human parts will behave truthfully is naive; where humans are involved, self interest invariably follows, and self interest is not always consistent with truth telling.

Bandwidth allocation in tactical data networks is one setting in which this problem is manifest.

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Approach

Economic mechanisms, such as markets and auctions, have a long history of being used for decentralized decision making by rational agents. We are studying the use of economic mechanisms to allocate computational resources. In these settings, systems are regarded as virtual economies, with network bandwidth, processor time, etc., regarded as scarce resources over which rational users will compete.

Our investigation focuses on the use of economic mechanisms to achieve an efficient allocation of network bandwidth for a tactical data network. We developed a realistic emulation of a tactical data network modeled on LINK-11, and developed a variant of a well-known auction mechanism to allocate network bandwidth for radar sensor fusion.

Foundations

Economic mechanisms offer a design language and mathematical foundation that is well suited to make human preferences first-class elements in the design of systems. A *mechanism* is an institution such as an auction, voting protocol, or a market, that defines the rules for how individuals are allowed to interact and governs the procedure for how collective decisions are made.

Mechanism design is the sub-discipline of game theory and economics concerned with designing institutions for optimal distributed decision making. The goal of mechanism design is to achieve prescribed and desirable global outcomes while accounting for the preferences of the individuals and organizations that affect and are affected by the outcome.

Computational mechanisms arise where individuals are computational agents working on behalf of humans.

Key Result

The study demonstrates that economic mechanisms are a feasible and interesting alternative to traditional systems approaches to resource allocation in systems that are highly dynamic; that involve many users engaged in different activities; and, where these users have varying and possibly competing objectives. Our result strongly suggests that *mechanism engineering*, the use of mechanism design as an engineering tool for developing large distributed systems, is a discipline waiting to emerge.

APPLYING MECHANISM DESIGN

Prior Work in Mechanism Design

Mechanism design is a rich field with deep roots in economics and game theory. In fact, the 2007 Nobel Prize in economics was awarded for work in this field[1]. *Computational* mechanism design is more recent, but is an area of active research. Examples include[2] mechanisms used to allocate processor cycles for scientific computing on the worldwide grid; for network routing; for allocating network capacity; for sensor fusion; for peer-to-peer systems; and for task allocation for autonomous robots. Mechanism design has already been used in practice. Examples include FCC radio spectrum auctions and real-time electricity markets. Also worth noting is that Google's keyword auction provided more than 98% of their $6.17B revenue in 2006. This hardly exhausts the subject of research and practice.

Background - Sensor Fusion on a Tactical Network

LINK-11 is a collection of digital data link protocols for communications among a number of participating units. Communication on the link takes place by round robin, designated roll call. Each unit reports when requested to do so by a participating unit that has been designated as Net Control Station.

At 2250 BPS for data (a bit more for voice) network bandwidth is a scarce resource in LINK-11. Even its successor LINK-16 has only 28.8 KBS for data. To conserve bandwidth, LINK-11 uses a reporting responsibility ("R^2") protocol where exactly one platform assumes R^2 for each radar contact, and only this platform reports data for that contact. While this approach has the virtue of conserving bandwidth, it sacrifices opportunities to fuse track data to improve the quality of the common operating picture.

Our concept is to *auction* additional quanta of bandwidth and allow the participating units themselves to decide which track data will be most valuable. A computational auction mechanism automates this process.

1 See http://nobelprize.org/nobel_prizes/economics/laureates/2007.

2 For complete citations see the full report of this work available at http://www.sei.cmu.edu/publications/documents/08.reports/08tr004.html.

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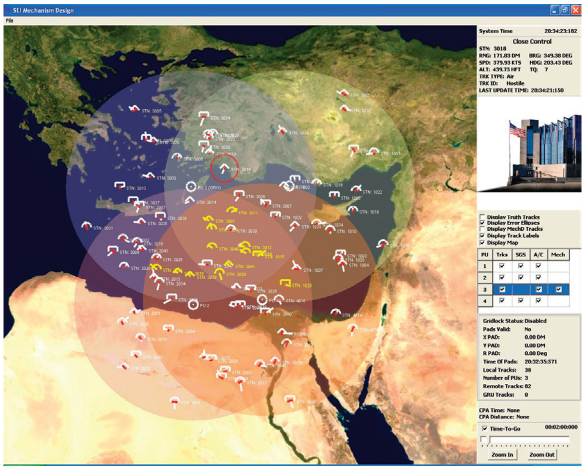

Figure 1: Track Data on the Tactical Display

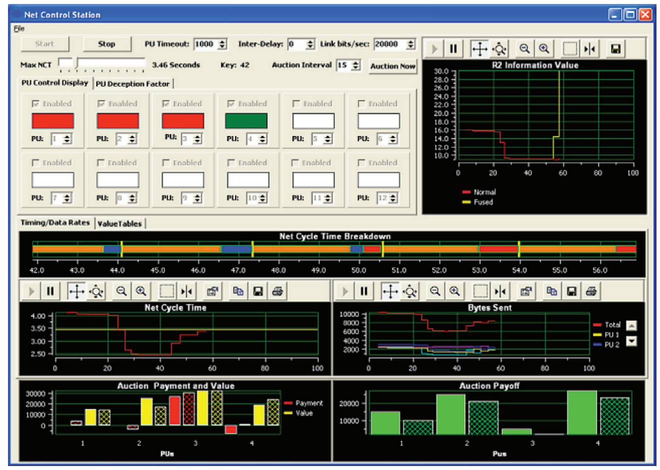

Figure 2: The Mechanism at Work

Designing the Mechanism

Designing an auction mechanism requires making a number of decisions, five of which are central to the auction design problem.

(1) Identify the scarce resources up for auction. We will auction *additional* quanta of bandwidth beyond the baseline R^2 protocol, so that *extra* track data can be transmitted for data fusion. This fusion will *improve* the quality of the common operating picture.

(2) Determine the criteria for desirable overall outcome. The mechanism must maximize the total information gain over all of the participants as a consequence of auctioning off spare bandwidth. Information gain is a quantifiable measure of the improvement in the *quality* common operating picture.

(3) Identify the participants' private information that will determine their outcome preferences. Participants have private information about which tracks they can see and about the quality of their track data. Participants *will* misrepresent their private information to the auctioneer if doing so will induce an outcome that is more favorable than if they tell the truth[3].

(4) Represent participant preferences in a payoff structure. Each participant is driven by self-interest. Self-interest stems from this hypothesized, but plausible, doctrine:

- Survivability of the individual participant depends on the survivability of the battle group, which in turn depends on maximizing information gain of the whole group.
- "After action reviews," which lead to promotions and other rewards, use marginal contribution to total information gain as an important evaluation criterion.

This incentivizes every participant to maximize their contribution to the group's information gain rather than increasing one's own information gain.

The incentivized payoff structure for the bandwidth auction is defined in Eq.1, which reflects each participant's marginal contribution to total information gain, where u_i and v_i are payoff and value functions for participant i, respectively; Z is the information that participant i has for all tracks; F^* and F_{-i}^* is the optimal bandwidth allocation with and without participant i included in the auction, respectively.

Total information gain—the needs of the many

$$u_i(Z,F^*) = v_i(Z,F^*) - \left[\sum_{j\neq i} v_j(Z,F^*_{-i}) - \sum_{j\neq i} v_j(Z,F^*)\right]$$

Value accrued: Information gain for participant i

Net value accrued: Payoff for participant i—the needs of the individual

Value cost: Payment made by participant i

The above doctrine incentivizes each participant to maximize its payoff; and, its payoff is maximized by maximizing the information gain of the whole group.

(5) Define the auction rules. An auction defines the bidding rules, the resource allocation approach, and the "payments" made by each participant for the resource they receive.

We used the Vickrey-Clarke-Groves (VCG) mechanism as our starting point. The VCG auction is a generalization of the second price sealed bid auction[4]. The VCG auction has the key property of "incentive compatibility," which ensures that each participating unit will maximize their payoff only by truthfully revealing their private information.

The result is that the needs of the *individual* are aligned with the needs of the *many*. This is the "trick" of mechanism design.

3 Deception is a real possibility in coalition force settings. In any case, truthfulness cannot be assumed by a robust computational mechanism.

4 Bids are secret and the winner pays second-highest bidder's bid.

Observing the Mechanism

Figure 2 depicts a snapshot of the portion of the "Net Control Station" interface used to study the auction at runtime.

The vertical, two-headed arrow labeled "NCT allocated…" shows the quantum of bandwidth auctioned for the purpose of data fusion. The horizontal bar labeled "Steady state R^2 reporting" shows how bandwidth is used, and includes the cost of running the auction itself. The auction is run periodically, for example once every 15 network cycles.

The *economic outcome* for one auction is shown at the bottom of Figure 2. In this example, participating unit 3 (PU 3) gains the most information but also makes the largest payment. PU 3's payment represents its adverse impact on the other participants. That is, if PU 3 were *not* in the auction, its payment (red bar) would be distributed as information gain (yellow bar) among the remaining participants.

Improvement in the quality of the common operating picture as a result of this auction is shown by the yellow "fused" tracks displayed in Figure 1. The error ellipse for these tracks (shown in red on each track) has been substantially reduced (that is, their accuracy has been increased) as a result of the auction. Net Control Station can also be used to study the effects of deception or other forms of strategic manipulation by platforms (not shown).

Summary

Centralized decision and control is mismatched with today's large-scale, distributed systems. Economics is tailor-made for the kinds of decentralized decision making required by network-centric systems. Computational mechanisms bring economic theory to the realm of software engineering to address robustly the issues of human incentives in decentralized decision making. The discipline of mechanism engineering, on par with performance engineering, safety engineering, etc., is waiting to emerge.