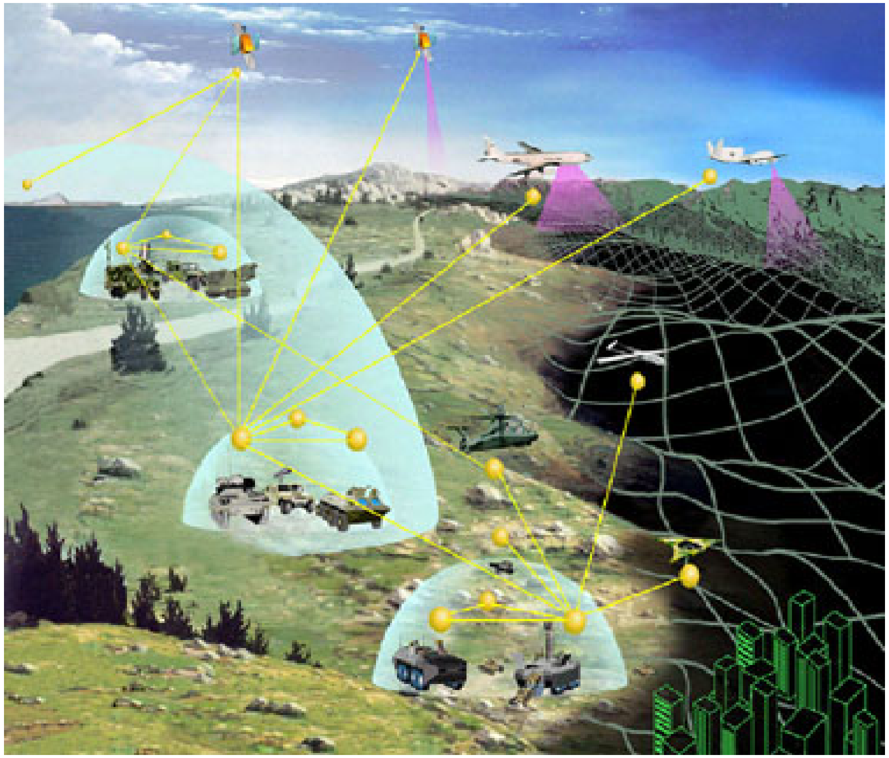
A Study on
The Network as Economy

The Premise

- Modern technological networks are on a collision course with human organizations, both civilian and military:
  - conflicts arise in all stages: design, configuration, and operations
  - conflicts with regulatory and C2 constraints
  - competing financial and other incentives
- Time is ripe to integrate economic thought into networking
  - current technology isolated from human goals and constraints
  - we must manage and design networks in their broader contexts

Network-centric Operations are at Risk



- Increasingly pervasive networking capability
- Network configuration complexity is increasing
- Network speed and pace-of-change are increasing
- Traditional network management is expensive and inflexible:
  - significant % of soldiers in Iraq
  - overprovisioning
  - centralized control
  - need skilled people at the nodes
  - assume stable environment

Economic networking is a key enabler of network-centric operations

Modern Networks are Economic Systems (whether we like it or not)

- Highly decentralized and diverse
  - allocation of scarce resources; conflicting incentives
- Disparate network administrators operate by local incentives
  - network growth; peering agreements and SLAs
- Users may subvert/improvise for their own purposes
  - free-riding for shared resources (e.g. in peer-to-peer networks)
  - spam and DDoS as economic problems
- Regulatory environments for networking technology
  - for privacy and security concerns in the Internet
  - need more "knobs" for society-technology interface

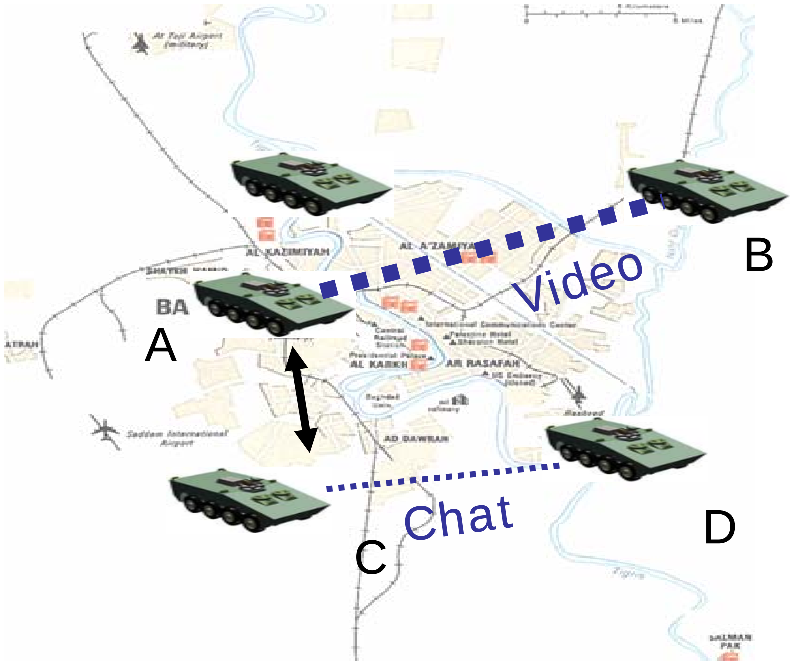
Economic Principles Can Provide Guidance

- Markets for the exchange of standardized resources
  - goods & services
  - prices encode exchange rates, compress info
  - efficiency and equilibrium notions for performance measurement
- Game theory, competitive and cooperative
  - strategic behavior and the management of competing incentives
- Learning and adaptation in economic systems
  - different and broader than traditional machine learning
- Certain nontraditional topics in economic thought
  - behavioral and agent-based approaches
- Active research at the CS-economics boundary

Two Illustrative Scenarios

Problem: Scarce Wireless Resources

- The Setting:
  - ad-hoc, wireless networking in tactical military environments
- The Problem:
  - resource allocation (e.g, bandwidth)
- How is it Solved Now?
  - priorities/constraints manually pre-assigned
  - traditional (centralized) optimization
- Why is it Economic?
  - scarce resources and multiple objectives
  - distributed, autonomous actors with competing/aligned incentives
    - human: commander-soldier
    - tech: video vs. chat
    - resolution should depend on situation
  - must balance individual incentives with collective mission



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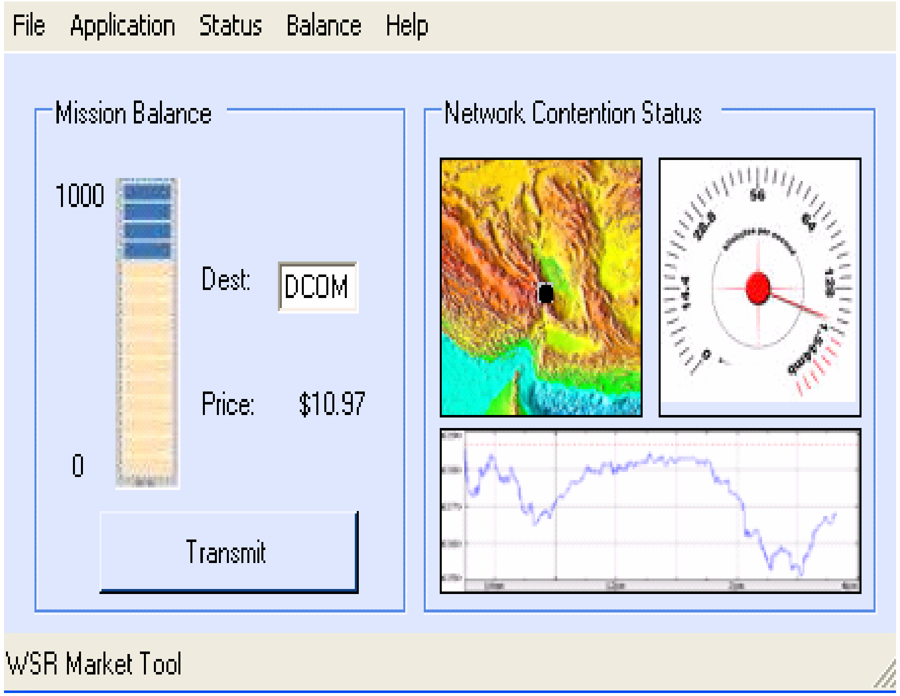
An Economic Solution:
A Wireless Bandwidth Market

- Goods Being Exchanged:
  - local bandwidth: the right to transmit a certain volume at a certain place and time
- Currency:
  - a virtual currency paid in exchange for local bandwidth
- Allocations:
  - dynamic budgets for units and individuals
  - top-down assignment through military chain of command
- Pricing Mechanism:
  - local adjustment according to local supply and demand
- Human-System Interface:
  - communication devices showing current cost of transmission

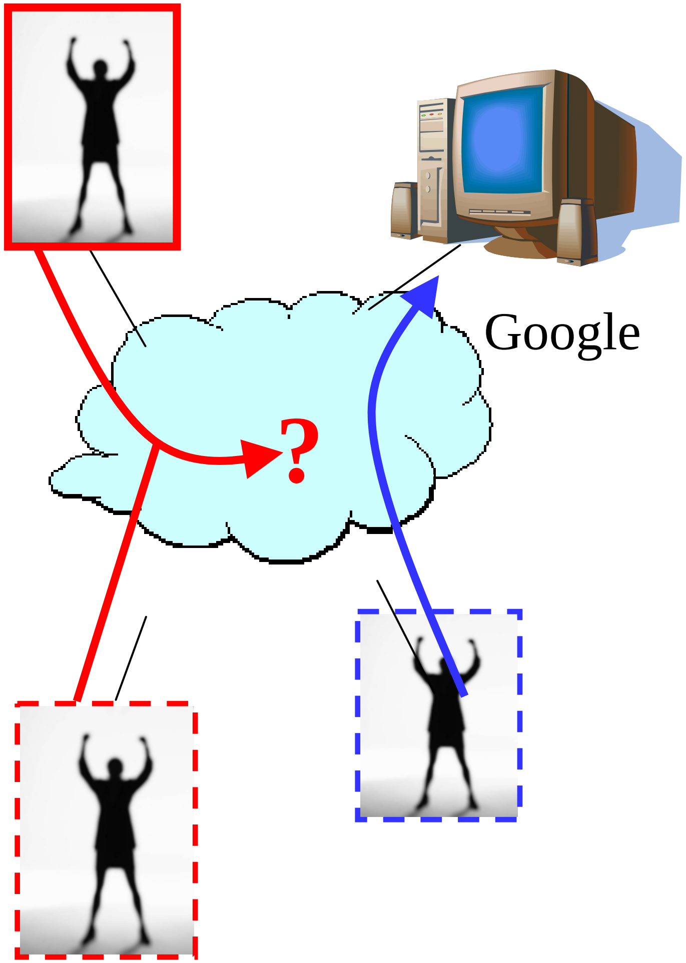


Problem: Network Troubleshooting

- The Setting:
  - large, distributed networks of autonomous systems
  - rich peering and customer-provider relationships
  - includes both the Internet and military networks
- The Problem:
  - rapid diagnosis & repair of performance, reliability, and security problems
  - acquiring global information to troubleshoot
- How is it Solved Now?
  - it isn't
  - phone calls between NW operators, ping and traceroute, CERT advisories
- Why is it Economic?
  - distributed actors with competing/aligned incentives
  - real economic incentives to learn external network status (e.g. improve security, performance)
  - disincentives to reveal local information "for free"

An Economic Solution:
A Network Diagnostics Exchange

- Goods Being Exchanged:
  - local network status information
  - outputs of diagnostics
  - e.g. SNMP queries, output of SNORT rules, data feed subscriptions,…
- Currency:
  - real money (e.g. USD)
  - could also support barter exchange
- Allocations:
  - actual current assets (cash and info)
- Pricing Mechanism:
  - bid-ask limit order matching process
- Human-System Interface:
  - initially: human participants (e.g. NW operators) in an electronic market
  - eventually: protocols purchasing and acting on information



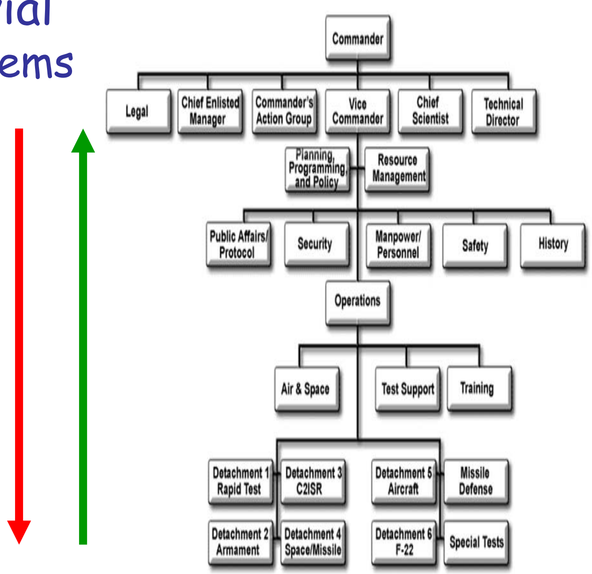
Other Network Problems Amenable to (or Requiring) Economic Approaches

- Dissemination of information:
  - situation awareness, sensor networks, target tracking,…
- Peering relationships in commercial networks
- Routing optimization based on multiple constraints
- Quality-of-Service
- Investment planning in networks:
  - using price signals to drive network growth

Research Challenges

Research Challenges for Economics

- Virtual currency and human incentives
  - need to design an interface between the two
  - military apps: tie virtual currency to org goals and reporting structure
    - allow deficit spending with accountability
    - bidirectional information flow via prices and allocations
- Practical market design
  - successful markets require infrastructure
    - legal system, regulatory bodies, settlement clearinghouses,…
  - designing infrastructure for new markets is nontrivial
    - integration with existing technological and social systems
    - little guidance from traditional economics
- Complexities
  - creating liquidity (avoiding Optimark)
  - crashes, bubbles, and speculation
  - middlemen and aggregators (e.g. Akamai)
  - options, futures, and other derivatives



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Practical Market Design

- Successful markets require infrastructure
  - legal system, regulatory bodies, settlement clearinghouses,…
- Designing infrastructure for new kinds of markets is nontrivial
  - integration with existing technological and social systems
  - little guidance from traditional economics
- Settlement mechanisms and penalties
  - WRM: tied to informal human processes, trust and authority reln's
  - NDX: traditional
- Quality control
  - NDX: verifiability/accuracy of information
  - commodity futures contracts
- Centralized inputs ("fed rates")
  - WRM: commander budget allocations
- Regulatory oversight
  - NDX: vetting of participants

Complexities

- Creating Liquidity (Avoiding Optimark)
  - WRM: demand not an issue; monopoly provider of supply
  - NDX: expect presence of (automated) market-makers
- Crashes, Bubbles and Speculation
  - WRM:
    - tight, centralized control of capital
    - bubbles more problematic than crashes; allow deficit spending
  - NDX:
    - not (initially) consumer investment vehicles; a private and controlled market
    - but may drive corporate speculation
- Middlemen and Aggregators
  - NDX:
    - expect potentially significant aggregation (e.g. Akamai);
    - may need mechanisms to control resale and piracy
- Options, Futures, and Other Derivatives
  - in NDX, for standard risk management/hedging practices
  - futures may also play role in WRM (guaranteed transmission)

Learning, Adaptation and Robustness

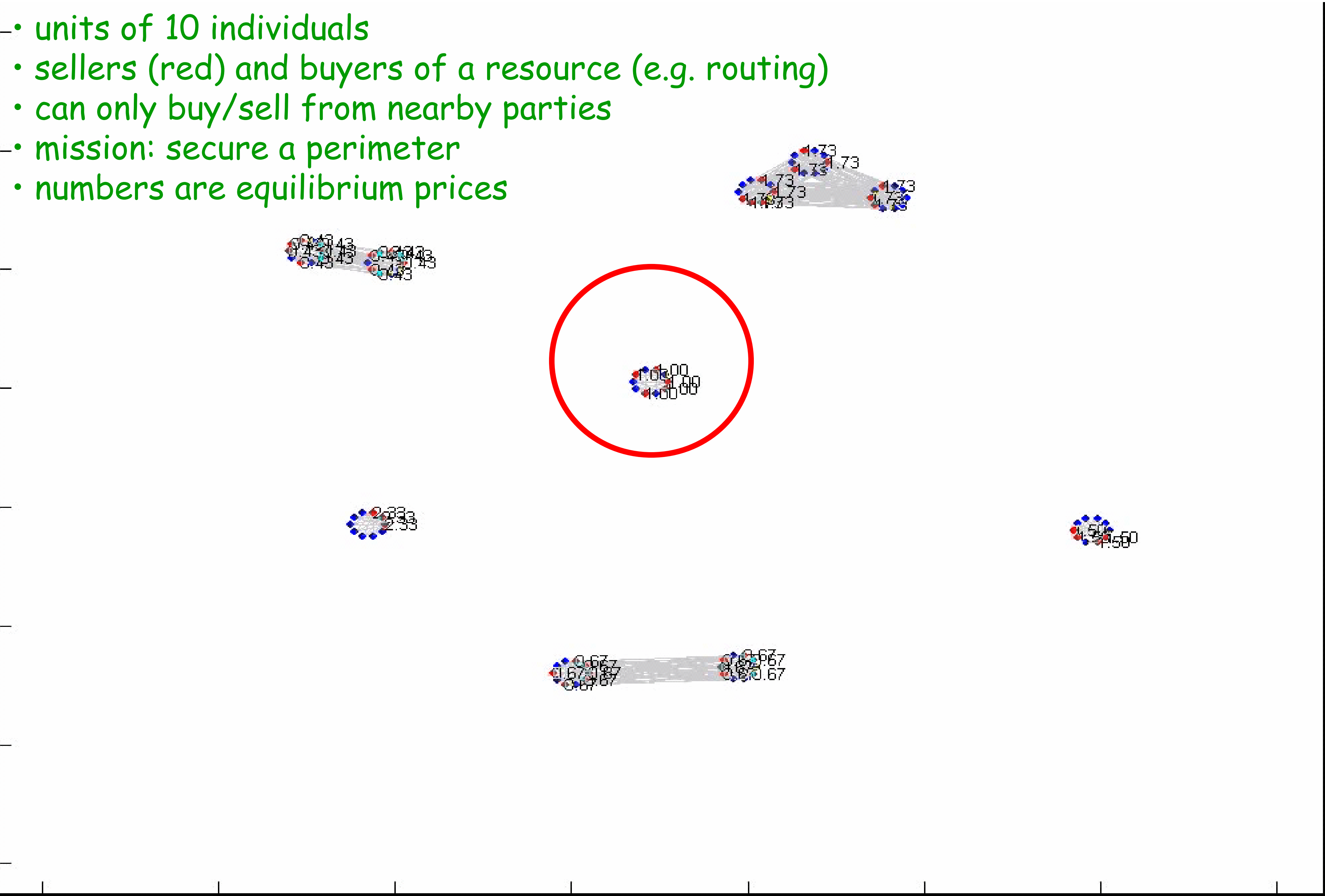
- Adaptation at all levels will be necessary and inevitable
- Networks will be more robust due to economic incentives
  - richer information availability
  - faster dissemination
  - alignment of technology and incentives
- Learning can be used to:
  - predict network properties and behavior (without buying the information)
  - change network behavior: routing, admission & congestion control, etc.
  - change economic behavior: what goods to buy and sell, at what prices
- Learning technology:
  - effective today for single-agent prediction problems
  - require significant research to extend to multi-agent adaptation
  - behavioral considerations
  - learning in games, price discovery/adjustment processes,…

Network Structure

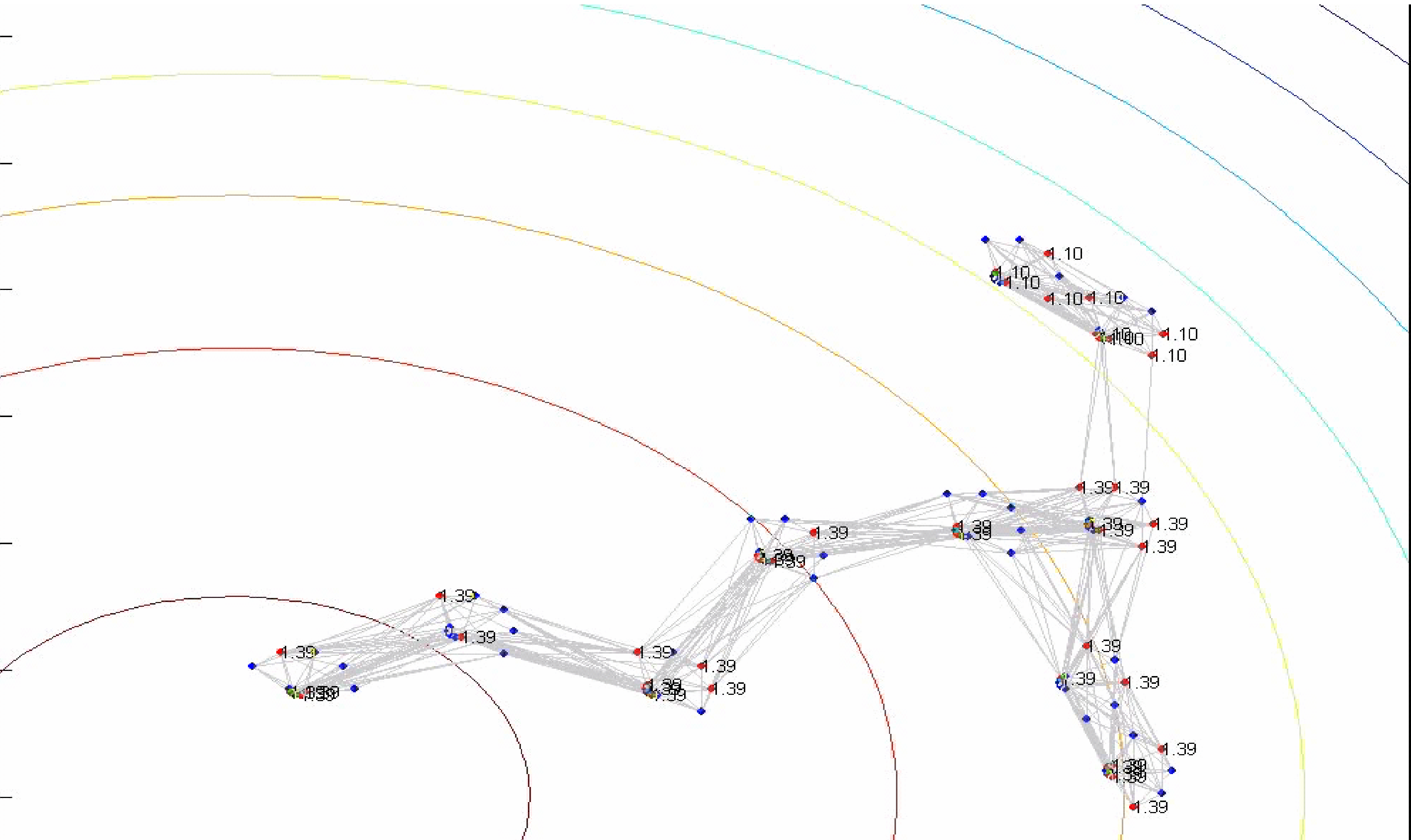
- Overwhelming bulk of economic thought assumes complete connectivity
  - centralized markets and exchanges, open competition, global info
  - imply no variation in prices
- In wireless scenario, network structure will be
  - potentially sparse
  - determined by the physics of transmission, terrain, physical movement…
- How will this network structure influence
  - equilibrium & stability
  - adaptive behavior
  - prices and performance
  - robustness

Distributed Allocation of Scarce Resources: Interaction of Movement and Prices

- units of 10 individuals
- sellers (red) and buyers of a resource (e.g. routing)
- can only buy/sell from nearby parties
- mission: secure a perimeter
- numbers are equilibrium prices



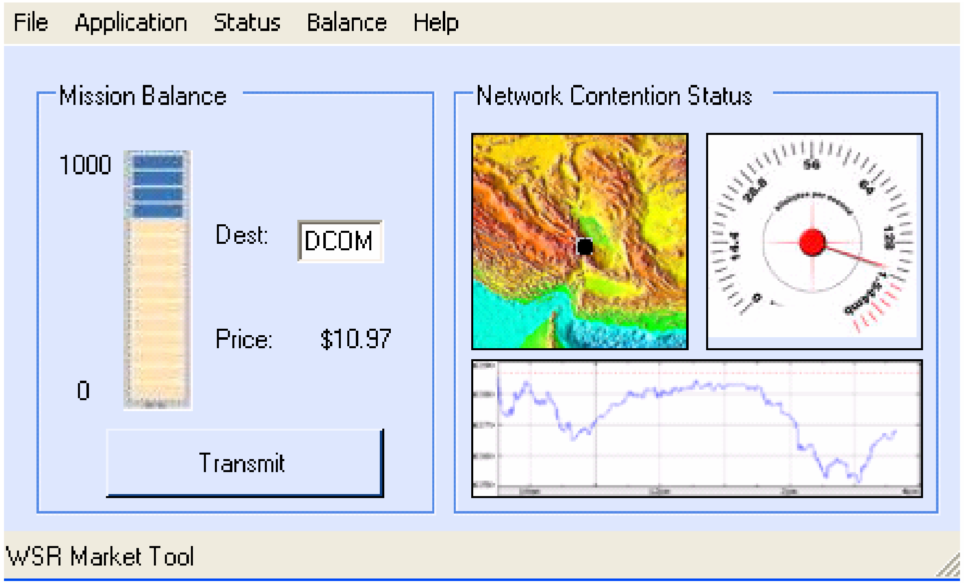
Distributed Allocation of Scarce Resources: Incorporating a Terrain Model



Challenge Problems

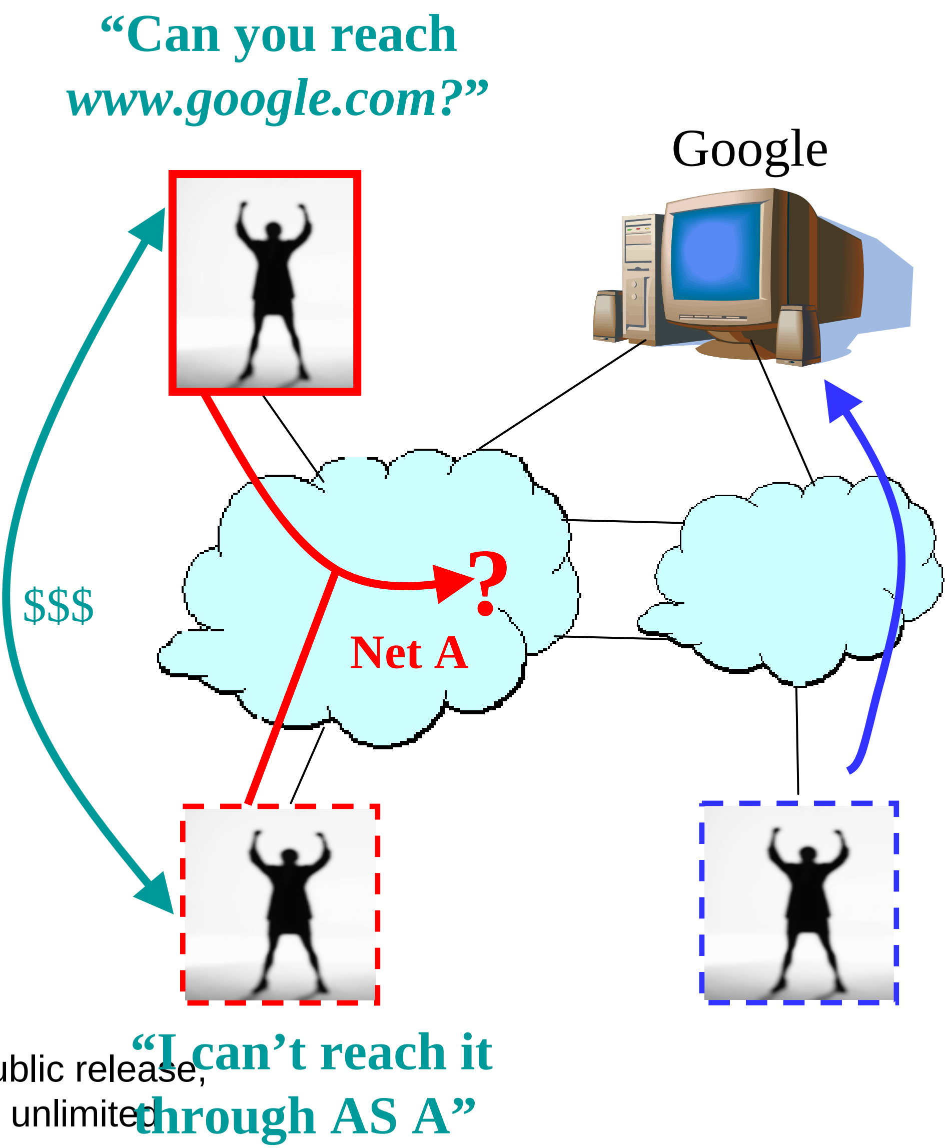
WRM Prototype

- System:
  - capacity market system & interface
  - resource allocation subsystem and protocols
- Experiments:
  - urban ops field test scenario in Ft Irwin
  - Drexel SWAT running FBCB2 SA, IP voice
- Participants:
  - units training for urban ops
- Metrics:
  - MOE: mission succeeds
  - MOE: sum RI-RP-RT
  - MOP: price volatility
- Goals:
  - RI-RP-RT within 20% of red-teamed hypothetical optimum



NDX Prototype

- System:
  - peer-to-peer exchange
  - pay to launch remote probes
  - combine to identify root cause
- Experiments:
  - on-demand diagnosis
  - fault injection in an overlay
  - "in the wild" on the Internet
- Participants:
  - volunteer users
  - initially with virtual currency
- Metrics:
  - successful diagnosis
  - fast, accurate, and efficient
  - increasing # of participants
  - engagement of providers
- Goals:
  - live and active NDX market
  - liberating the diagnostic data



Why Now and Why DARPA?

- Networking/economics collision is happening and causing pain
  - must be addressed boldly and aggressively
  - DARPA has an opportunity that does not exist in commercial sector
    - both in scale and ability to implement "mixed" systems
- Military NW technology on bleeding edge where "traditional" approach may not even exist
  - e.g., hard power constraints
  - opportunity/need for systems mixing competitive & cooperative elements
- Relevant research has traction, is gaining momentum
  - algorithmic mechanism design and computational game theory
  - distributed optimization
  - strategic learning in multi-agent systems
  - engineering based on economic principles

Conclusions

- There are compelling arguments for the use of economic methods and viewpoints in the design of modern networks
- Resource-constrained military networks are especially promising targets for this approach
- Economic thought provides new methods and metrics
  - market efficiency
  - market liquidity
  - Price of Anarchy
  - GDP and fed rate for complex networks?
- There is important foundational work providing initial traction, but many open research and implementation issues