Design and Implementation of the Bio-Networking Architecture

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Overview

- Introduction to the Bio-Networking Architecture
  - Motivations
  - Biological concepts applied
  - General design of the Bio-Networking Architecture
- Simulation Study of
  - Static adaptation scenarios
  - Dynamic adaptation scenarios
- Empirical implementation of the Bio-Networking Architecture
  - Design, implementation and measurements of the Bio-Networking platform
  - On-going work

Introduction to the Bio-Networking Architecture

Motivation

- Computer network environment is becoming larger and more complex.
- Need a self-organizing network that supports
  - *scalability* in terms of # of objects and network nodes,
  - *adaptability* to changes in network conditions,
  - *availability/survivability* from massive failures and attacks,
  - *simplicity* to design and maintain.
- **Our solution: *apply biological concepts and mechanisms to network application design***
  - Biological systems have overcome the above features.
    - e.g. bee colony, bird flock, fish school, etc.
- The Bio-Networking Architecture is a new framework
  - for developing large-scale, highly distributed, heterogeneous, and dynamic network applications.

Biological Concepts Applied

- Decentralized system organization
  - Biological systems
    - consist of autonomous entities (e.g. bees in a bee colony)
    - no centralized (leader) entity (e.g. a leader in a bird flock)
      - Decentralization increases scalability and survivability of biological systems.
  - The Bio-Networking Architecture
    - biological entities = cyber-entities (CEs)
      - the smallest component in an application
      - provides a functional service related to the application
      - autonomous with simple behaviors
        - » replication, reproduction, migration, death, etc.
        - » makes its own behavioral decision according to its own policy
    - no centralized entity among CEs

- Emergence
  - Biological systems
    - Useful group behavior (e.g. adaptability and survivability) emerges from autonomous local interaction of individuals with simple behaviors.
      - i.e. not by direction of a centralized (leader) entity
      - e.g. food gathering function
        - » When a bee colony needs more food, a number of bees will go to the flower patches to gather nectar.
        - » When food storage is near its capacity, only a few bees will leave the hive.
  - The Bio-Networking Architecture
    - CEs autonomously
      - sense local/nearby environment
        - » e.g. existence of neighboring CEs, existence/movement of users, workload, availability of resources (e.g. memory space), etc.
      - invoke behaviors according to the condition in a local/nearby environment
      - interacts with each other

- Lifecycle
  - Biological systems
    - Each entity strives to seek and consume food for living.
    - Some entities replicate and/or reproduce children with partners.
  - The Bio-Networking Architecture
    - Each CE stores and expends *energy* for living.
      - gains energy in exchange for providing its service to other CEs
      - expends energy for performing its behaviors, utilizing resources (e.g. CPU and memory), and invoking another CE's service.
    - Each CE replicates itself and reproduce a child with a partner.

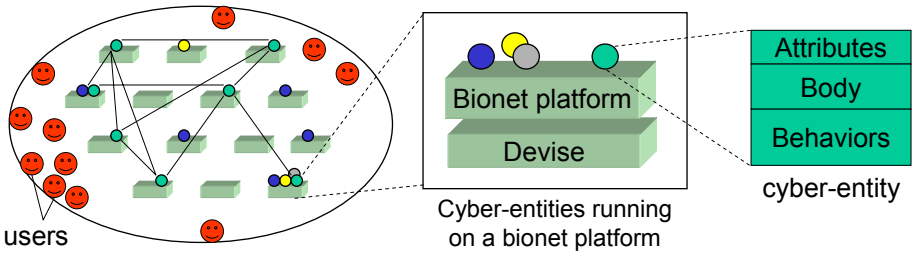
- Evolution
  - Biological system
    - adjusts itself for environmental changes through species diversity and natural selection
  - The Bio-Networking Architecture
    - CEs evolve by
      - generating behavioral diversity among them, and
        - » CEs with a variety of behavioral policies are created by human developers manually, or through mutation (during replication and reproduction) and crossover (during reproduction)
      - executing natural selection.
        - » death from energy starvation
        - » tendency to replicate/reproduce from energy abundance

- Social networking
  - Biological systems (social systems)
    - Any two entities can be linked in a short path through relationships among entities.
      - not through any centralized entity (e.g. directory), rather in a decentralized manner.
      - six decrees of separation
  - The Bio-Networking Architecture
    - CEs are linked with each other using *relationships*.
      - A relationship contains some properties about other CEs (e.g. unique ID, name, reference, service type, etc.)
    - Relationships are used for a CE to search other CEs.
      - Search queries originate from a CE, and travel from CE to CE through relationships.
    - The *strength* of relationship is used for prioritizing different relationships in discovery.
      - A CE may change its relationship strength based on the degree of similarity between two CEs.
      - The stronger relationship is likely to lead a query to a successful discovery result.

Design Strategy of the Bio-Networking Architecture

- Separate cyber-entity (CE) and Bio-Networking Platform (bionet platform),
  - Cyber-entity (CE)
    - mobile object (agent) that provides any service
  - Bionet platform
    - middleware system for deploying and executing CEs
- Implement CE and bionet platform in Java

CE's Structure and Behaviors



- Attributes
  - ID
  - Relationship list
  - Age
  - …etc.
- Body
  - Executable code
  - Non-executable data

- Behaviors
  - Energy exchange and storage
  - Communication
  - Migration
  - Replication and reproduction
  - Death
  - Relationship establishment
  - Social networking (discovery)
  - Resource sensing
  - State change

Research Strategy

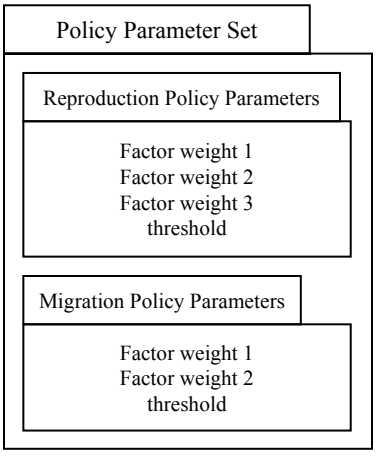
- Simulation work to investigate if applied biological concepts work well
  - Adaptation through evolutionary process
  - Social networking (decentralized discovery)
- Empirical implementation work to deploy the Bio-Networking Architecture on actual networks.
  - Implementation of the Bio-Networking Platform (bionet platform)

Simulation Study: Adaptation and Evolution

Introduction

- **Goal**:
  - To optimize the behaviors of cyber-entities (replication and migration) in order to make a network application more efficient
- **Approach**:
  - Applying evolutionary mechanisms in the cyber-entity

Reproduction and Migration Policies



Gene model for a cyber-entity

Migration Policy Factors used in this simulation

Request Rate Factor	Encourage a CE to migrate toward a requesting user
Resource Cost Factor	Encourage a CE to migrate toward a cheaper resource cost node
Population Density Factor	Encourage a CE to migrate away from a node when the number of CEs is increasing
Wander Factor	Encourage a CE to randomly chose a node to migrate to.

Migration Policy:

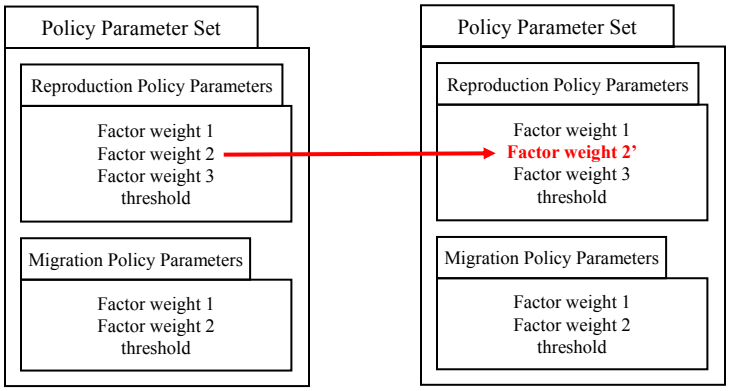
$$If \sum_{i=0}^{n} W_i \cdot F_i > M, \ then \quad Migrate$$

Evolutionary Mechanisms

- Evolutionary mechanisms are incorporated in **replication** and **reproduction**, generating diverse cyber-entity entities.
- Natural selection (energy) keeps fitter cyber-entities while eliminating inefficient cyber-entities.
- The repeated interaction between generating diversity and natural selection enables evolution.

Evolutionary Mechanisms

- In replication, mutation occurs.
  - Change a weight of a factor



Evolutionary Mechanisms

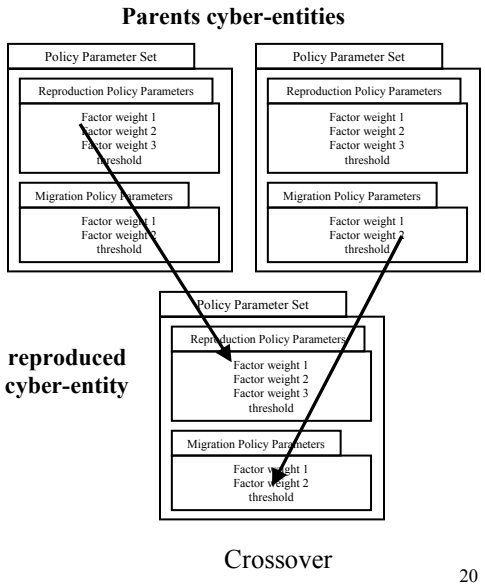
- Reproduction involves two steps.
  - Local partner selection and crossover (possibly with mutation)
- Local Partner Selection
  - Reproducing entity selects a partner on the platform or nearby platforms,
  - based on three selection criteria: waiting time, hop count, and energy efficiency

- *Waiting time:* the average time of a service request being stored at a platform before the cyber-entity processes the service request
- *Hop count:* the average distance between a requesting user and the cyber-entity that processes the request
- *Energy efficiency:* The consumed energy / [acquired energy + consumed energy].

- A partner entity is probabilistically selected according to
  - these performance of the reproducing entity and,
  - predefined performance requirements.
  - e.g., when the partner selecting cyber-entity is inefficient to satisfy a pre-defined level of energy gain, maximizing energy efficiency may be chosen as the objective goal to improve.

Evolutionary Mechanisms

- Crossover
  - Behavior policies of parents cyber-entity are mixed and transferred to the next generation (reproduced cyber-entity).
- Mutation
  - Can occur in a same way as in replication.



Simulation Configurations

Cyber Entities

- 10000 energy unit given
- Placed on the center
- Request processing time: 0.2 sec
- Die at the age of 1 simulated hour
- 3000 energy units are given by the reproducing parent to its child

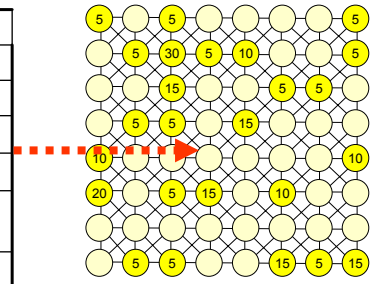
Platforms

- Network topology: 8x8
- Charge 5 energy units to an entity for computing resources
- Charge 100 energy units for each behavior
- TTL set to 5 hop counts

User Request

- Constant request rate (number in the circle)
- Pay 10 energy units for a service (CE)
- Forwarded to the nearest CE (node)
- A maximum of 500 request messages stored in a node queue

	PR
R. Request Rate	**0.1**
R. Threshold	***0.5***
M. Request Rate Ratio	**1.0**
M. Resource Cost Ratio	**0.5**
M. Population Density Ratio	**1.0**
M.Wandering	**0.5**
M. Threshold	***2.0***

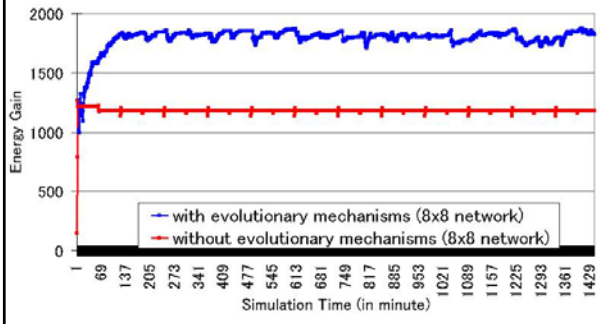


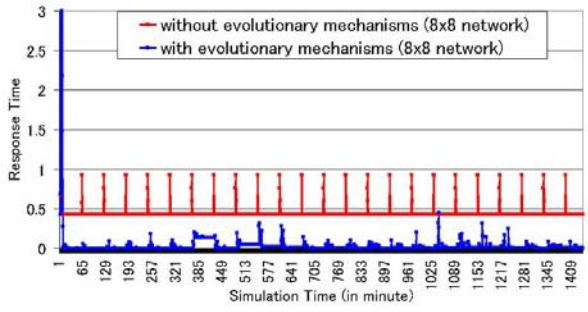
Simulated network and the user request rate / sec

Evaluation Criteria

- Response Time:
  - Waiting time of a service request at a platform and network delay of the request
- Hop Count:
  - The average distance between a requesting user and the cyber-entity that processes the request
- Energy Gain:
  - The difference between *acquired energy and consumed energy*.

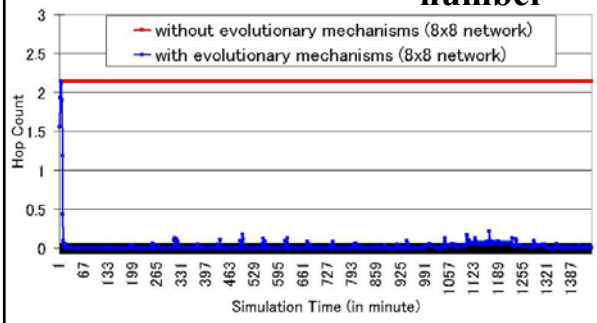
Performance of PR - Energy Gain and Response Time -

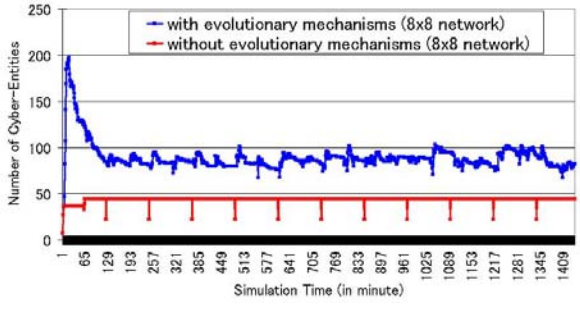




- **Energy gain is improved**: as time progresses, the cyber-entity's behavior is optimized through evolution.
- Evolution creates a cyber-entity that can actively migrate around networks, which finally finds new energy sources (user request).
- **Response time is also improved**: Successfully adjusted the number of cyber-entity as a result of optimization in reproduction behavior.

Performance of PR – Hop Count an a population number -





- **Hop Count is improved**: migration behavior is optimized. Cyber-entities weaken migration behavior once users are found (,since all the users never move.)
- Some simulated time later, **the total population number becomes stable**, and seems to converge to a certain number.

Simulation Summary

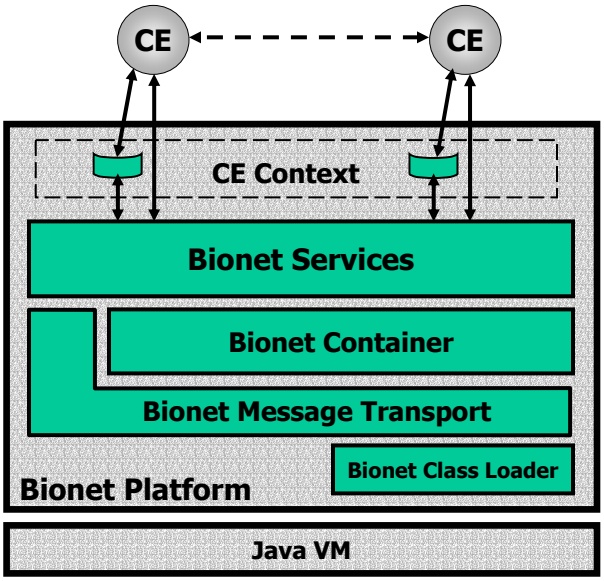
- Cyber-entities successfully evolve and adapt to simulation environments.
- (not shown today's talk, but) various types of cyber-entities and network environments are examined,
  - Randomly walking users
  - Different resource cost environment
  - Unstable network with topological changes

Bio-Networking Platform

The Bio-Networking Platform

- The Bio-Networking platform (bionet platform)
  - is a middleware system that provides reusable software components for deploying and executing cyber-entities.
    - abstract low-level operating and networking details (e.g. I/O, concurrency, messaging and network connection management) and,
    - provide a set of runtime services that CEs frequently use for
      - performing their services,
      - sensing network environment, and
      - invoking their biological behaviors.

Architecture of the Bio-Networking Platform



A *Cyber-entity (CE)* is an autonomous mobile object. CEs communicate with each other using FIPA ACL.

A *CE context* provides references to available bionet services.

***Bionet services* are runtime services that CEs use frequently.**

***Bionet container* dispatches incoming messages to target CEs.**

***Bionet message transport* takes care of I/O, low-level messaging and concurrency.**

***Bionet class loader* loads byte code of CEs to Java VM.**

Bionet Message Transport

- Bionet message transport abstracts low-level operating and networking details such as I/O, concurrency, messaging, network connection management.
  - Marshaling/unmarshaling of messages issued by a CE
    - GIOP/IIOP used currently
  - TCP connection setup and management
  - Message delivery on a TCP connection
    - One-to-one messaging, currently
    - One-to-many broadcasting/multicasting (future work)
  - Threading (thread pooling) to accept incoming messages

Bionet Container

- Bionet container dispatches incoming messages to target CEs.
  - Demultiplexing incoming messages
  - Dispatching incoming messages to target CEs
  - Creating CE references
  - Activating and de-activating CEs

Bionet Services

- CEs use bionet services to invoke their behaviors.
  - e.g. bionet lifecycle service when a CE replicates
- Each bionet platform provides 9 bionet services
  - Bionet Lifecycle Service
    - allows a CE to change its state.
    - maintains a thread pool that contains threads assigned to autonomous CEs
    - allows a CE to replicate itself and reproduces a child CE with a partner.
    - allows a CE to reproduce a child CE with a partner
    - Mutation and crossover during replication and reproduction
  - Bionet Relationship Management Service
    - allows a CE to establish, examine, update and eliminate their relationships with other CEs.

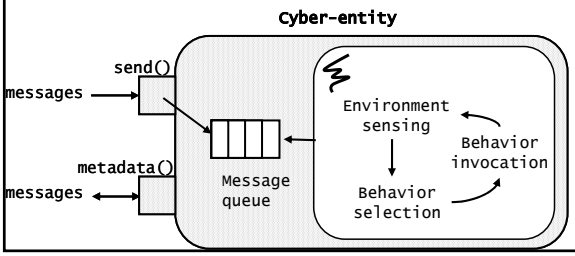
  - Bionet Energy Management Service
    - keeps track of energy level of the CEs running on a local platform.
    - allows a CE to pay energy for
      - invoking a service provided by another CE,
      - using resources, and
      - performing behaviors (i.e. invoking a bionet service).
  - Bionet Resource Sensing Service
    - allows CEs to sense the type, amount and unit cost of available resources (CPU and memory).
      - CPU availability = $N_{idle\_threads}/N_{max\_threads}$
        - » where $N_{idle\_threads}$ is the number of idle threads in a thread pool maintained by bionet lifecycle service, and
        - » $N_{max\_threads}$ is the max number of threads in the thread pool.
      - Memory availability = M_{free}/M_{max}
        - » where M_{free} is the amount of memory available on Java VM, and
        - » M_{max} is the max size of memory allocated to Java VM.
      - Resource unit cost is determined based on resource availability.

- Bionet CE Sensing Service
  - allows a CE to discover other CEs running on neighboring bionet platforms reachable in N hops (platform-level discovery).
    - N = 0; discovery of local CEs running on the same platform.
    - N > 0; discovery of remote CEs running on different platforms.
- Bionet Pheromone Emission/Sensing Service
  - allows a CE to leave its pheromone (trace) on a local platform when it migrates to another platform
    - so that other CEs can find the CE at a destination platform
  - allows a CE to let other CEs know of its existence by broadcasting its metadata.
    - Other CEs may come to interact with the CE or establish a relationship with the CE.

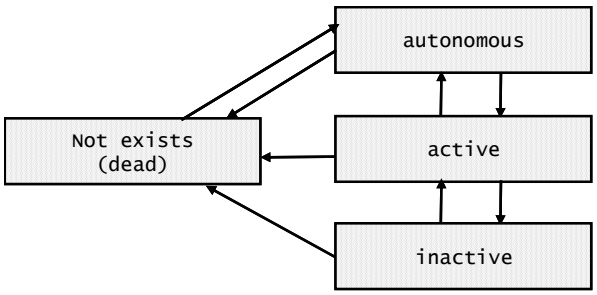
- Bionet Topology Sensing Service
  - allows a CE to sense the connectivity among neighboring bionet platforms reachable N hops.
    - proactive sensing
    - reactive sensing
    - hybrid sensing
    - static sensing
- Bionet Social Networking Service
  - allows a CE to search other CEs through their relationships (CE-level discovery).
- Bionet Migration Service
  - allows a CE to migrate to another bionet platform.

Cyber-entity

- CEs communicate with each other through:
  - **interface CyberEntity {**
    oneway void send(in string message);
    string metadata(); };
  - A subset of FIPA ACL with some extensions is used as a communication language.
    - encoded with XML
- Implemented as Java mobile code



- Each CE uses an individual thread to continuously
  - sense the nearby environment,
  - identify behaviors suitable for the current environment condition, and
  - invoke the most suitable behavior



Each CE may have 4 states during its lifetime.

It changes its state voluntarily; any CEs are not allowed to change another CE's state.

- An autonomous CE
  - receives messages from other cyber-entities.
  - continuously senses nearby environment and performs its behaviors.
  - runs on an individual thread; thus, expends energy continuously for using a thread (CPU) and memory space.
- An active CE
  - is ready for receiving messages from other cyber-entities, but
  - does not perform behaviors
  - consumes memory; thus expends energy continuously for using memory space.
- An inactive CE
  - is in "sleeping" state in which it is externalized into a file
  - does not expend energy because it does not consume any resources.

Implementation Status

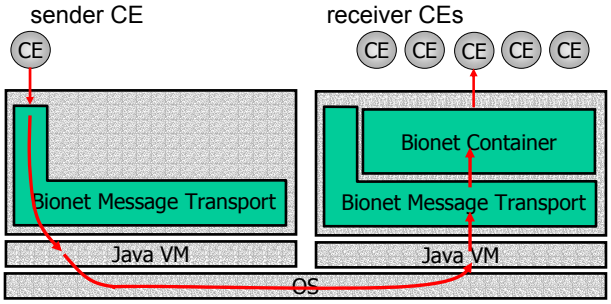
- Every component in the bionet platform has been implemented,
  - except the bionet topology sensing service.
  - Bionet message transport and bionet container are implemented based on the CORBA specification.
    - Our own CORBA implementation, called muORB
    - Publicly available CORBA implementation called JacORB
- Measurements and documentation underway
  - netresearch.ics.uci.edu/bionet/resources/platform/

Standardization Effort at OMG

- A goal of the OMG Super Distributed Objects (SDOs) working group is to
  - provide a standard computing infrastructure for highly distributed ubiquitous networking systems.
- SDO is a logical representation of a hardware device (e.g., PDA, AV device and refrigerator) and software component.
- Status:
  - The SDO RFI issued (‘00), and responses gathered (‘01)
    - from 10 organizations including UCI
  - The SDO white paper published (‘01)
  - The first RFP published (‘02).
    - the resource data model for SDOs and the interfaces that SDOs implement.
  - Hitachi, GMD Fokus and UCI will submit the joint revised specification in March ’03.
    - Several key constructs in the Bio-Networking Architecture have been reflected (e.g. CE’s attributes such as energy level, relationship, relationship attributes such as relationship strength)

Preliminary Measurement Results

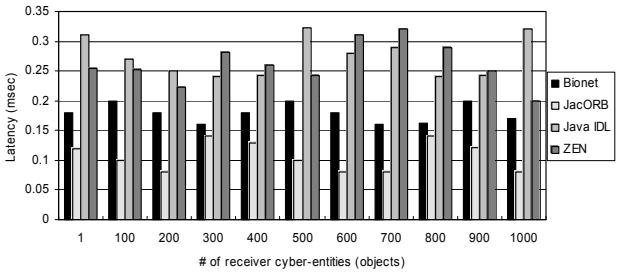
Message Transmission Latency



A sender CE dynamically selects a receiver CE at random, and sends an empty string message to the selected CE.

Measurements were conducted within a single machine with Java 1.4 VM, Win XP, and 1GHz Pentium 3 CPU. 64 MB heap allocated to each Java VM

- What we measured
  - Latency for message transmission between two CEs
    - How long it takes for a CE to send a message to another CE?
- Overhead sources to message transmission
  - Marshaling a message issued by a sender CE,
  - TCP connection setup,
  - message delivery on the connection,
  - message dispatching to a receiver CE, and
  - unmarshaling of an incoming message.

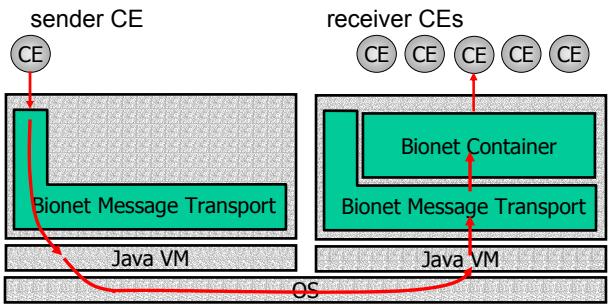


A single sender CE and a range of receiver CEs (1, 100, …1000) were deployed.

Bionet platform was compared with existing distributed object platforms implemented in Java.

- Measurement results and observations
  - Bionet message transport and container are fairly efficient and comparable with existing distributed object platforms.
    - Message transmission latency was 0.17 msec when 1,000 receiver CEs were deployed.
  - Bionet message transport and container are scalable in terms of the number of receiver CEs.
    - Latency is relatively constant when the number of CEs grows, rather than it increases linearly (the average of latency was 0.179 msec.).
      - In general, increasing the # of receiver CEs increases the effort to establish TCP connections to receiver CEs (in sender side) and demultiplex/dispatch incoming messages to target CEs (in receiver side).
    - Implementation techniques such as connection sharing and hash-based demultiplexing work well.

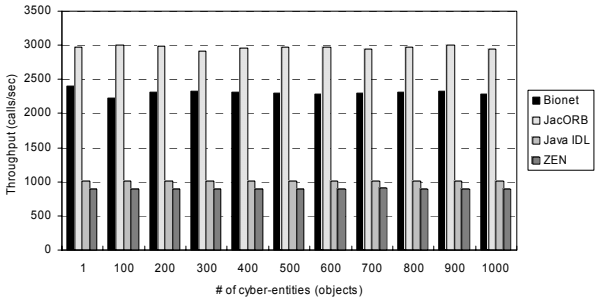
Message Throughput



A sender CE selects a receiver CE at random before a measurement, and sends empty string messages to the selected CE.

Measurements were conducted within a single machine with Java 1.4 VM, Win XP, and 1GHz Pentium 3 CPU. 64 MB heap allocated to each Java VM

- What we measured
  - throughput of a CE
    - How many messages a CE can receive and process in a second?
- The throughput is dominantly affected by
  - message demultiplexing in bionet container.



A single sender CE and a range of receiver CEs (1, 100, …1000) were deployed.

Bionet platform was compared with existing distributed object platforms implemented in Java.

- Measurement results and observations
  - The throughput of a CE on a bionet platform is competitive with existing distributed object platforms.
    - Throughput was 2279.99 messages/sec when 1,000 receiver CEs were deployed.
  - Bionet container are scalable in terms of the number of receiver CEs.
    - Increasing the number of receiver CEs increases the demultiplexing effort. Throughput remains relatively constant as the number of receiver CEs grows (2309.27 messages/sec in average), rather than it increases linearly.
    - Implementation technique of hash-based demultiplexing works well.

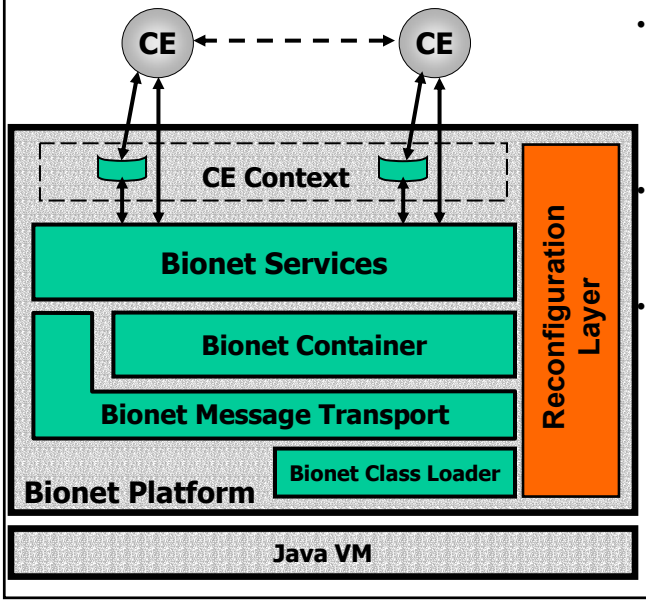
On-going Work

Empirical adaptability of CEs

- Empirical implementation of evolutionary adaptation mechanism
  - Has implemented a framework to define and manipulate behavioral policies (factor, weight and threshold values).
  - Now implementing CE's behavior selection mechanism
    - to calculate weighted sum of factor values, compare it with a threshold value, and invoke a corresponding behavior.
  - Will evaluate empirical adaptability of CEs on actual network environments soon.

Reconfigurability of Bionet Platform

- Motivations to reconfigure bionet platform
  - Every user and application does not require every functionalities/services provided by the bionet platform.
  - Every network node probably cannot deploy all the components in the bionet platform due to resource constraint.
- Approach to reconfigure middleware
  - Compose middleware as a set of components.
  - Middleware
    - sense its context such as available resources and systems current configuration.
    - determine a strategy to reconfigure middleware according to the obtained context.
    - execute the determined reconfiguration strategy.
- Our goal is to investigate the adaptability of networking system by making not only network applications but also underlying middleware systems to be reconfigurable.



- Design (re-design) bionet services and major functionalities in a bionet service as middleware components
- Insert a reconfiguration layer into the bionet platform
- The reconfiguration layer manages and controls middleware components.
  - Dependency mgt.
  - Consistency mgt.
  - Query/lookup for middleware components
  - Loading/unloading middleware components
  - Environment sensing

Thank you

- All the papers/documents are available at:
  - **Project web site:**
    - **netresearch.ics.uci.edu/bionet/**
  - **Bionet simulator**
    - **netresearch.ics.uci.edu/bionet/resources/evolution_simulator/**
  - **Bionet platform**
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