Adaptive Spatiotemporal Node Selection in Dynamic Networks

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Outline

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Introduction

• A dynamic network is a set of potentially mobile devices (nodes) in a specific geographic area, which forms spontaneously rather than being configured in advance.

• Devices offer services to each other, (eg. sensing, accelerated computation, and data storage).

• Each device must share its resources (e.g., I/O device access, CPU time, disk space, etc.).

• Uses of such networks:
  • Traffic monitoring,
  • Distributed search and surveillance
  • Grassroots launching of new mobile services
  • Community-based participatory research

• Unlike a traditional sensor network, the nodes of a dynamic network may all have different owners who seek compensation for the use of their resources.

• Assume a virtual currency system to incentivize service provision; units of currency are called "credits".

• Nodes advertise a price in credits for each service they offer, which they can change in response to demand or resource scarcity (such as battery charge level).

• Applications purchase services, and must stay within their budgets.
• Motivation:
  • Dynamic network applications have spatiotemporal properties that can be exploited to achieve a better overall program outcome.
• Lead to a novel strategy for expressing and satisfying an application's node selection needs.
• Sarana framework used
• What is Sarana?
  • A high-level parallel programming architecture for dynamic networks
  • Enables applications to express their spatiotemporal properties,
  • Uses these to perform effective, automated node selection and scheduling under a user-specified budget.
  • Properties can be holistic, describing the desired spatial or temporal distribution of selected nodes.
  • They can also be dynamic, describing desired run-time events (computational results or sensor readings), so that Sarana can target devices likely to yield such events.
Contributions:

• Language:
  • Employs a parallel loop construct to describe distributed computations.
  • Each iteration visits a node and invokes a service.
  • Allows to express spatiotemporal properties of the application and constructs
  • Application can evaluate the results of a distributed computation and provide dynamic feedback
  • Chose a language over a library implementation of our new programming abstractions
    • Allow a simpler specification of spatiotemporal properties, enable compile-time analyses and future optimizations.

• Prototype:
  • Sarana implementation consists of
    • Compiler,
    • Run-time system,
    • Adaptive space-time aware scheduler

• Three driver examples
  • a collaborative image capture and analysis application (Amber Alert),
  • a straight forward sensing application (Bird Tracking),
  • a space and time-dependent image sampling application (Crowd Estimation).
Spatiotemporal Properties

• **Clustering:** Desirable events may exhibit spatial and/or temporal locality.
  • In spatial clustering node selection is directed towards promising geographic sub-regions.
  • In temporal clustering node visits are increased in the immediate aftermath of a positive event.

• **Dispersal:** The presence of one event at a particular time and place may make it unlikely that another desired event would occur nearby.
  • In spatial dispersal, node selection is directed away from unpromising geographic regions
  • In temporal dispersal, node visits are discouraged in the immediate aftermath of a negative event.

• **Coverage:** An application may need a representative sample of sensor readings over a geographic region or time period.
  • With spatial coverage, a geographic region is divided into equal-area sectors and each sector is sampled (if possible).
  • With temporal coverage a time period is divided into equal intervals and a sample is taken at each interval (if possible).

• **Synchronization:** An application may need a set of sensor readings at the same time or place.
Figure 1: Spacetime patterns that can be expressed in Sarana. Shading indicates spacetime subregions that should be preferred in node selection.
Sample Applications

- **Amber Alert** (spatiotemporal clustering).
  - Amber Alert is a program run by U.S. law enforcement agencies to find abducted children, particularly during the crucial first few hours after the abduction has been reported.
  - If a search target is identified, the image is sent to participating smartphone and PDA users near where the image was taken.

- **Bird Tracking** (spatial dispersal, weighted events).
  - This application tries to record bird songs in a target area (e.g. a forest) using a network of microphones.

- **Crowd Estimation** (temporal synchronization, spatial coverage).
  - This application tries to take photos that will be used to estimate the number of people at a large outdoor gathering.
Solution Framework

**Language Constructs**

- Sarana adds network macro-programming extensions to the Java programming language.
  - A spatial region is an abstract set of devices observing a specific service in a geographic area.

- *visit* statement is similar to a parallel FORALL loop: loop iterations may be executed in parallel on separate nodes of the dynamic network.
  - *visit* loops do not contain synchronization or data dependences other than those generated by reduction variables.
  - A loop body may contain report statements, which signal user-defined events.

- Events describe the outcome of individual loop iterations
  - Raising an event will correspond to the determination that an iteration produced useful results.
  - A floating-point value between zero and one indicates the weight of the event, 1.0 being the strongest possible feedback.

- Clauses to specify spatiotemporal heuristics to guide node selection and scheduling.
  - Clauses can have parameters; most clauses take an event name and a radius.

- At least one spatial and one temporal heuristic will be employed.
  - Default strategy is to choose locations and times where iterations can be executed at low cost.

- A Sarana service is represented by a persistent Java object which is accessible to the calling program through the variable declared in a *visit* statement.
Sarana working

• **Compiler**
  • The Sarana compiler is based on *javaparser*,
  • performs a source to source translation from Sarana to Java.
  • A Sarana application program is divided into independently schedulable code segments called *tasks*.
  • The current task division scheme creates a distinct task for the main program and the body of every visit, and places each task into its own Java class (the *task-class*).

• **Program Execution**
  • **Run-Time System Components**: The Sarana run-time system is a persistent background process that runs on every Sarana-enabled node, and includes several components.
    • The *directory* is a network-wide system that maintains a map of Sarana-enabled nodes, their geographic locations, and their available services and service costs.
      • It currently consists of a central server and client modules on each node,
      • To be converted to a distributed, peer-to-peer model in the near future.
    • The *policy controller* restricts the use of a node's resources by setting prices for the node's services, according to an administrator defined configuration.
    • The *service manager* instantiates and supervises Sarana services installed on a device.
    • The *process manager* supervises the execution of individual tasks received from injection nodes.
      • It monitors tasks to ensure that they do not exceed their cost budgets.
    • The *code distribution manager* handles up-load of Java class files to remote execution sites.
    • The *system call handler* provides common services to local applications only (e.g., obtaining GPS location or currently remaining credits).
Execution

• Execution begins on the injection node with the main task.

• When a visit loop is reached, the run-time scheduler is invoked, tasks corresponding to the body of the loop are distributed to the selected nodes, and the system waits for results to be returned.

• Intelligent scheduling of visit loops is accomplished through the use of *incremental execution*.
  
  - When executing a visit loop on which a cluster-space or disperse-space clause has been specified, Sarana first conducts a *probing pass*.
  - The desired spatial region divided into several equal-sized sectors, and a suitable node in each sector is selected. Execution of the loop provides partial results and event reports.
  - Based on these reports and the spatiotemporal heuristics chosen for the visit, an expected value is assigned to each node in the space.

• Sarana then constructs a schedule for spending the remaining credits allocated to this loop.

• The schedule is a tree which describes the set of nodes to be visited during this loop, the number of credits to be spent at each, and sub-schedules for each nested loop to be initiated at each visited node.

• The schedule construction is an optimization problem where every node has an expected cost and an expected value.

• To avoid wasting credits, a node will not be selected for a particular loop if its geographic location does not make sense.

**Schedule Construction.** Sarana's schedule optimizer employs a greedy heuristic

  1. Query the directory for *targets*, exclude targets that have been visited on recent probing passes.
  2. Construct a minimum-cost plan: a tree containing just enough targets at each nesting level.
  3. For each remaining target, compute a value density: the ratio of the target's expected quality contribution to its service cost.
  4. Insert the targets into a priority queue ordered by decreasing value density.
  5. Remove potential targets from the queue and consider them for inclusion in the plan.
Sample Code

SRDecl ::= spatialregion space = service @ region
ReportStmt ::= report event [= weight]
VisitStmt ::= visit Range Member Timeout
Range ::= [ (minNodes, maxNodes) ]
Member ::= provider in space
Timeout ::= [ by timeout ]
Heuristics ::= Heuristic {}, Heuristic
Heuristic ::= Spread | Random | Sync
CtrlSpace ::= (cluster-space | disperse-space) Ctrl
CtrlTime ::= (cluster-time | disperse-time) Ctrl

Figure 2: Syntax specification.

1. spatialregion cameraSpace = CameraService @ Circle(150); // cameras within 150 m of injection
2. sum_reduction int displayedCount = 0;
3. collection_reduction ArrayList<ImageBlob> foundSet = new ArrayList<ImageBlob>();
4. // at least 1 camera, events cluster within 20 m and 1 sec, overall deadline is 50 sec
5. visit camera in cameraSpace by 30: cluster-space(GOODPIC, 20), cluster-time(GOODPIC, 1) {
6.   ImageBlob image = camera.takePhoto();
7.   spatialregion analysisSpace = AnalysisService @ Circle(150); // analysis nodes within 150 m of camera
8.   or_reduction boolean success = false;
9.   visit (1,1) analyzer in analysisSpace { // exactly 1 analysis node
10.  success |= analyzer.analyze(image); }
11. if (success) {
12.    report GOODPIC; // quality obtained from this execution
13.    foundSet.add(image);
14.    spatialregion displaySpace = DisplayService @ Circle(30); // displays within 30 m
15.    visit (1,10) display in displaySpace {
16.      display.show(image);
17.      displayedCount += 1; } } }

Figure 3: Amber Alert code skeleton.

1. spatialregion microphoneSpace = MicrophoneService @ Circle(1000);
2. collection_reduction ArrayList<SoundBlob> foundSet = new ArrayList<SoundBlob>();
3. visit microphone in microphoneSpace : disperse-space(NOISE, 50) {
4.   SoundBlob sound = microphone.recordSound();
5.   if (isNoise(sound)) {
6.     report NOISE = sound.getVolume(); // stay further away from louder noises
7.   } else if (isBird(sound)) {
8.     foundSet.add(sound); } }

Figure 4: Bird Tracking code skeleton.

1. spatialregion cameraSpace = CameraService @ Circle(1000); // cameras within 1 km of injection
2. collection_reduction ArrayList<ImageBlob> foundSet = new ArrayList<ImageBlob>();
3. visit (100,120) camera in cameraSpace by 300: spread-space, sync-time {
4.   ImageBlob image = camera.takePhoto();
5.   foundSet.add(image); } }

Figure 5: Crowd Estimation code skeleton.
Experimental Evaluation

• **Physical Prototype:**
  
  Sarana runtime system installed on 11 Nokia N810 tablet PC devices, 14 Neo FreeRunner (Openmoko) smartphones, and one Apple Macintosh laptop running OS X 10.5.

  N810 and FreeRunner both have GPS receivers. All devices have microphones.

  The N810 has a built-in camera

  Camera service simulated on the FreeRunner, returns predefined image.

  For lack of real birds, input to the microphone was simulated.

• **Simulation environment:**
  
  Simulations performed on a cluster of 79 Dell workstations running Fedora Red Hat 4.1.2 Linux.

  A master control program distributes tasks to each workstation and monitors their output.

  Each physical machine runs multiple instances of the Sarana run-time system, representing separate nodes in a dynamic network.

  At start, Master server reads a configuration file which describes the spatial region in which the trial will be conducted.

  • This file describes the set of devices present, the services provided by each, and the initial locations of each.
  
  • Services relying on physical hardware- camera or microphone- simulated.
  
  • Nodes offering the camera service given stock images that will be returned when a photo is “taken"

    • Image returned varies with time

    • Each camera can take a photo up to once per second.
Results & Evaluation

• Spatiotemporal Clustering: Amber Alert

**Physical trials:**
25 randomly placed camera/display nodes and one injection node. cost of each service: camera, 10; analysis: 2; display, 5
Experimental trial lasts for 30 seconds overall.
Target subjects visible for three seconds or less, starting at a randomly selected time.
9 such subjects: possible to obtain 27 photos of these
Exhaustive exploration: taking a photo with every camera
as frequently as was possible, and trials were performed with
5% (214) to 35% (1501) of the budget necessary to do this.
For each budget, a trial was run 10 times, and the results of
these 10 trials were averaged.

**Simulation:**
90 randomly placed camera/display nodes, 9 analysis
nodes, and one injection node.
10 such subjects, and it is possible to obtain 90 images
Trials were performed with 10% (1500) to 100% (15000) of the
budget necessary to exhaustively explore the space. For each
budget, a trial was run 30 times in each of 5 randomly generated
configurations, and the results of these 150 trials were averaged.

*Performance Improvement*: up to 745% measured, 117% simulated
Results & Evaluation

• Spatial Dispersal and Weighted Events: Bird Tracker

Performance Improvement:
38% measured
142% simulated

Figure 7: Bird Tracking with spatial dispersal, with and without adaptive scheduling.
Results & Evaluation

• Spatial Coverage and Temporal Synchronization: Crowd Estimation

![Graphs showing spatial coverage and temporal synchronization performance improvement.](image)

**Performance Improvement:**
86% measured
209% simulated

Figure 8: Crowd Estimation with temporal synchronization, baseline algorithm (spread-space only) and sync-time. Graphs show the maximum number of photographs timestamped in any time window of the given size.
Conclusion

• Performance of resource-constrained dynamic network applications can be significantly improved by exploiting their spatiotemporal properties.

• This improvement can take the form of better outcomes for the same resource budget, or comparable outcomes at much lower cost.

• Sarana is the first system that allows a user to specify spatiotemporal heuristics at the language level that are harnessed at run time to adaptively schedule the execution of an application on a set of mobile nodes.

Future Work

• Investigating possible spatiotemporal optimizations and their impact on program performance.

• Privacy and security are clearly important issues in any mobile network environment where resources might be shared.

• Resource-constrained systems will require tradeoffs between the degree of security and the resources required to maintain that degree of security.

• Framework can be extended to allow the programmer to express security preferences effectively