Report Number: WUCS-01-28

2001-01-01

Network Abstractions for Context-Aware Mobile Computing

Gruia-Catalin Roman, Christine Julien, and Qingfeng Huang

Context-Aware computing is characterized by the ability of a software system to continuously adapt its behavior to a changing environment over which it has little or no control. Previous work along these lines presumed a rather narrow definition of context, one that was centered on resources immediately available to the component in question, e.g., communication bandwidth, physical location, etc. This paper explores context-aware computing in the setting of ad hoc networks consisting of numerous mobile hosts that interact with each other opportunistically via transient wireless interconnections. We extend the context to encompass awareness of an entire neighborhood within the... Read complete abstract on page 2.

Network Abstractions for Context-Aware Mobile Computing

Gruia-Catalin Roman, Christine Julien, and Qingfeng Huang

Complete Abstract:

Context-Aware computing is characterized by the ability of a software system to continuously adapt its behavior to a changing environment over which it has little or no control. Previous work along these lines presumed a rather narrow definition of context, one that was centered on resources immediately available to the component in question, e.g., communication bandwidth, physical location, etc. This paper explores context-aware computing in the setting of ad hoc networks consisting of numerous mobile hosts that interact with each other opportunistically via transient wireless interconnections. We extend the context to encompass awareness of an entire neighborhood within the ad hoc network. A formal abstract characterization of this new perspective is proposed. The result is a specification method and associated context maintenance protocol. The former enables an application to define an individualized context, one that extends across multiple mobile hosts in the ad hoc network. The latter makes it possible to delegate the continuous reevaluation of the context and the performance of operations on it to some middleware operating below the application level. This relieves application development of the obligation of explicitely managing mobility and its implications on the components's behavior.

Network Abstractions for Context-Aware Mobile Computing

Gruia-Catalin Roman, Christine Julien and Qingfeng Huang

WUCS-01-28

October 2001

Department of Computer Science
Washington University
Campus Box 1045
One Brookings Drive
St. Louis MO 63130

Network Abstractions for Context-Aware Mobile Computing

Gruia-Catalin Roman, Christine Julien, and Qingfeng Huang
Department of Computer Science
Washington University
Saint Louis, MO 63130
{roman, julien, qingfeng}@cs.wustl.edu

ABSTRACT

Context-aware computing is characterized by the ability of a software system to continuously adapt its behavior to a changing environment over which it has little or no control. Previous work along these lines presumed a rather narrow definition of context, one that was centered on resources immediately available to the component in question, e.g., communication bandwidth, physical location, etc. This paper explores context-aware computing in the setting of ad hoc networks consisting of numerous mobile hosts that interact with each other opportunistically via transient wireless interconnections. We extend the context to encompass awareness of an entire neighborhood within the ad hoc network. A formal abstract characterization of this new perspective is proposed. The result is a specification method and associated context maintenance protocol. The former enables an application to define an individualized context, one that extends across multiple mobile hosts in the ad hoc network. The latter makes it possible to delegate the continuous reevaluation of the context and the performance of operations on it to some middleware operating below the application level. This relieves application development of the obligation of explicitly managing mobility and its implications on the component's behavior.

Keywords

Mobile computing, ad hoc network, context-aware computing, specification

1. INTRODUCTION

The ubiquity of mobile computing devices opens the user's computing environment to a rapidly changing world where the network topology, or the physical connections between hosts in the network, must be constantly recomputed. Software must adapt its behavior continuously in response to the changing context.

Context-aware computing first came to the forefront in the early 1990's with the introduction of small, mobile computing devices. Initial investigations at Olivetti Research Lab and Xerox PARC laid the foundation for the development of more recent context-aware software. Olivetti's Active Badge [21] uses infrared communication between badges worn by users and sensors placed in a building to monitor movement of the users in order to forward telephone calls to the user's location. PARC's PARCTab system [20], released in 1993, also uses infrared communication between users' palm top devices and desktop computers. It uses location information to allow applications to adapt to the user's environment. Applications developed for PARCTab perform activities ranging from simply presenting information to the user about his current location to attaching a file directory to a room for use as a blackboard by users in the room.

More recent context-aware applications serve as tour guides by presenting information about the user's current environment. Cyberguide from Georgia Tech [1], and GUIDE from the University of Lancaster [7] are examples of two such systems. Fieldwork tools [14] automatically attach contextual information, e.g., location and time, to notes taken by a researcher in the field. Memory aids [17] record notes about the current context that might be useful to the user at a later time.

In the later 90's, frameworks built to support the development of context-aware applications began to be developed. Among the best known systems is Georgia Tech's Context Toolkit [19], which uses an object oriented approach to separate the sensing, gathering, and interpretation of the contextual information for each user.

Much of the work to date is restrictive in its use of contextual information [4]. These systems use only information that can be monitored directly by the host running the software. One can easily imagine a situation where a mobile user has an interest not only in contextual information collected by his mobile unit, but also by other units, even units that are not directly connected. Mobile units in the network become part of other hosts' contexts. Additionally, the type of contextual information available to users and applications has been of limited types. For example, the guide tools define context strictly as the user's location, and most context-aware systems are built upon similarly rigid structures. Context-aware applications should have the ability to define individualized contexts; such definitions may extend beyond our current vision of context and may need to include a rich amalgamation of facets of the environment. An application in such an environment should be permitted to supply a definition of its desired context; subsequent operations issued by the application would be performed only in the subset of the network satisfying the application's definition. This requires mechanisms for computing an application defined context that may include distant hosts reachable only indirectly through an ad hoc routing protocol.

Our work starts from the premise that development of mobile applications can be simplified by allowing developers to specify a context specific to their application's needs and by adopting a notion of context that extends to an entire reachable set of neighboring hosts. The research issues we pose in this paper address both specification and implementation concerns relating to context definition and maintenance. First is the question of how to facilitate a formal specification of context, one that is general, flexible, and amenable for use in ad hoc settings. The solution maps all nodes in the ad hoc network to points in an abstract multi-dimensional space and defines context as the set of all such points whose distance from the point of reference (i.e., that denoting the host carrying the application of interest) does not exceed some bound that can change throughout the lifetime of the application. We will show that a number of useful contexts can be defined in this manner. Second is the issue of being able to maintain the specified context and to carry out operations on it. The protocol presented in this paper builds upon ideas from on demand ad hoc routing but constructs and dynamically maintains a tree over a subnet of neighboring hosts and links whose attributes contribute to the definition of a given context, as required by an application on a particular mobile host. Context sensitive operations are carried out through a cooperative effort involving only hosts that are part of a given context.

The paper is organized as follows. Section 2 provides a more detailed problem definition. Section 3 discusses the abstractions required to create a context specification. Section 4 presents a protocol that computes and maintains a specified context. Section 5 provides some discussion of the protocol followed by conclusions in Section 6.

2. PROBLEM DEFINITION

Ad hoc mobile networks may contain many hosts and links with varying properties. These hosts and links and their properties define the context for an individual host in the network. The behavior of an adaptive application running on a host in an ad hoc network depends on this continuously changing context. A major difference between our approach and previous work in context-aware computing is the breadth of our definition of context. Our goals include broadening the context available to a host to include not only those properties that can be measured directly by a host, but also properties of other reachable hosts and properties of links among them. However this has the potential to greatly increase the amount of contextual information available, and therefore an application running on a host should specify the precise context that interests it based on the properties of hosts and links in the network. The application should also specify a bound that defines the size of the context it chooses to operate in. For example, an ad hoc network on a highway might extend for hundreds or even thousands of miles. A driver in a particular car, however, may be interested only in gas stations within five miles. Because we aim to provide both a manner for an application to specify its context and a protocol that computes and maintains the context according to this specification, we need to allow the context specification to remain as general and flexible as possible while ensuring the feasibility and efficiency of the protocol to dynamically compute the context.

In summary, we want to provide an application running on a particular host, henceforth called the reference, the ability to formally specify a context that spans a subset of the ad hoc network in existence at any given point in time. Abstractly, the context can be viewed as a subnet around the reference host and the properties of that subnet's components (hosts and links). In most cases these properties will not be only those of the raw hardware but also properties associated with hosts or links by virtue of the applications they support.

Throughout the discussion of the context specification and the protocol that achieves it, we will refer to the following scenario. A family on a cross country vacation would like information about their current environment. That is, while they are driving, they would like to be constantly aware of the points of interest in their near vicinity. When the children are hungry or the car needs gas, they would like to be able to quickly discover restaurants or gas stations nearby. The context they will operate on is defined as the five miles around them. As we build the context specification and the protocol, we will indicate how each piece would be achieved for this scenario.

3. CONTEXT SPECIFICATION

Extending the availability of contextual information beyond a host's immediate scope requires an abstraction of the network topology and its properties. After specifying some constraints including the application's specific definition of distance and a maximum allowable distance, an application on the reference host would like a qualifying list of acquaintances to be generated. That is:

> Given a host, α, in an ad hoc network, and a positive value, D, find the set of all hosts, Q_α, such that all hosts in Q_α are reachable from α, and for all hosts, β, in Q_α, the cost of the shortest path from α to β is less than D.

To build this list we first must define a shortest path and how to determine the cost of such a path. Costs derive from quantifiable aspects of the reference host's context. In any network, both hosts and the links between them have quantifiable attributes that affect in many different ways the communication in the network. We abstract these properties by combining the quantified properties of nodes with the quantified properties of the links between them to achieve a single weight for each link in the network. An application has the freedom to specify which properties define the weights of links. A simple example of a weight is for each link to have a weight of one. This will allow us to count the number of network hops between two nodes in the network.

Once a weight has been defined and calculated for each link in the network, a cost function specified by the application can be evaluated over these weights to determine the cost of a particular path in the network. Continuing the network hop count example, the cost function specified by the application would be the sum of the weights of the links along a path. Because the weight of each link is one, the number of hops from the source of the path to that node determines the cost at that node. In a real network, however, multiple paths may exist between two given nodes. Therefore we will build a tree rooted at the reference host that will include only the lowest cost path to each node in the network. We will see later in this section and in the next section that this tree and the paths composing it have several nice properties that we will take advantage of in building and maintaining the tree.

Because we aim to restrict the scope of an application's context, calculating the lowest cost to every node in the network is not reasonable. To limit the context specification, we require the application to specify a bound for its cost function. Nodes to which the cost is less than the bound are included in the context. For the hop count example, an entire context specification might be written as: all nodes which can be reached in fewer than five hops.

We will start with this bound on the context specification and work backwards, dissecting the tree built to see from where each step derives. We will provide formal descriptions of the weights, cost function, and bound for the cost function. Throughout these descriptions, we will revisit the hop count example as a tool for understanding the definitions. We will also introduce more complex and realistic examples to demonstrate the power and generality of the approach. At each point, we will also explain how the specification applies to the family vacation scenario.

3.1 Ensuring Boundedness

We will see later how an ad hoc network can be represented as a graph, $G = (V, E)$ with weighted edges. We will create a tree rooted at a reference node that includes only the shortest paths from the reference node to each other reachable node in the network. Given this tree representation and the shortest paths, we can define a bound. Any nodes for which the cost of the shortest path is greater than the bound are not included in the set of acquaintances. Again, in the network hop count example, hosts that are five or more hops away are not included.

The vacationing family also specifies a bound on their context. If they are currently driving through Minnesota, museums in Washington D.C do not interest them. Therefore, they restrict their context to be only other communicating nodes in the vicinity, specifically, within five miles.

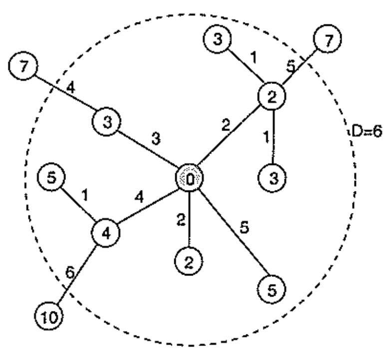


Figure 1: The bounded shortest path tree

Figure 1 shows a tree rooted at the shaded reference node, α. The weights on the links can be used to compute the cost of a given path, shown inside each node. Mechanisms for assigning these weights and calculating the cost of the paths will be discussed in later sections. This particular example shows a shortest path tree whose cost function simply sums the weights on a path. Figure 1 also shows the bound, D, indicated by the dashed line. Nodes inside the dashed circle are part of host α's acquaintance list, Q_α, while nodes outside the dashed circle are not part of this list and will not be included in queries over Q_α.

Notice that this bound is useful only if the value of the cost of the shortest path is strictly increasing as the path extends away from the reference node. That is, if we number the nodes on a path $\langle 1, 2, \ldots, i, \ldots, n \rangle$ and designate the value of the cost of node i as ν_i, then $\nu_i > \nu_{i-1}$. This guarantees that a parent in the tree is always topologically closer to the root than its children, i.e., that the cost of the path to the parent is always less than the cost to the child. If the cost of a path in the tree strictly increases as the distance from the reference node grows, the application can enforce a topological constraint over the search space by specifying the bound, D, over the value, ν, returned by the cost function. The lower level can stop propagating context building messages once it reaches a node on the path that has a distance (cost) greater than D. In the particular case shown in Figure 1, context building messages are no longer propagated once a node with a cost greater than 6 is reached.

Unfortunately, an ad hoc network does not look like a shortest path tree with the cost of each path labeled on the node. In the following section, we will show how to build the shortest path tree, given the cost of individual paths. Then we will discuss how to calculate the cost of a given path between two nodes in a graph using an application specified cost function. Finally, we will introduce the network abstraction that allows us to represent contextual information from the ad hoc network as weights on edges in this graph.

3.2 The Minimum Cost Path

In the next section, we will see that, given an application specified cost function, we can determine the cost of a path between two given nodes. The calculation of the cost of a path, P, originating at the reference node, α, will be represented as $f_\alpha(P)$. In an arbitrary graph, however, multiple paths may exist from a node, α, to another node, β, each with an associated cost. For each of these nodes, β, reachable from α, one of these paths is the shortest path. We call the length of this path $g_\alpha(\beta)$. That is, for all paths, P from α to β,

$$g_\alpha(\beta) = \min_{over\ all\ P\ from\ \alpha\ to\ \beta} f_\alpha(P)$$

There is a shortest path tree, T, spanning the graph representing the ad hoc network, rooted at the reference node, α. For all nodes, β, in this tree, the path from α to β in T has cost $g_\alpha(\beta)$.

Figure 2 shows the same shortest path tree as shown in Figure 1. This time, however, the bound is omitted, and the graph from which the tree was generated is shown in its entirety. The set of nodes is identical to that in Figure 1, but now more links and their weights are included. The links from Figure 1 are shown darkened; these are the links from the graph that make up the shortest path tree. Though the graph contains multiple paths from the reference node to each other node, the tree includes only the shortest path to each node.

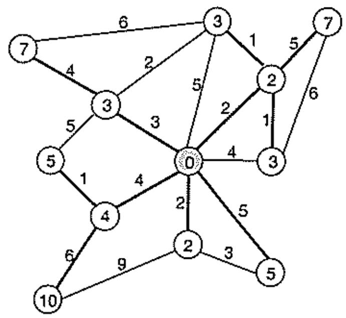


Figure 2: The logical network and shortest path tree

3.3 The Path Cost Function

The previous sections show that if we can define the cost of every path in a graph, we can compute the shortest path tree, T. We can then add a bound on the path cost to generate a set of acquaintances for a reference node. Given a logical view of an ad hoc network, $\overline{G} = (\overline{V}, \overline{E})$, in which each edge has a weight, we would like to assign a cost from the reference node, $\alpha \in \overline{V}$, to any other reachable node, $\beta \in \overline{V}$. An application running on the reference node specifies a cost function that provides instructions to the lower layer on calculating the cost of a given path in the logical network, $\overline{G}$. A path, $P = \langle \overline{v_0}, \overline{v_1}, \cdots, \overline{v_k} \rangle$ indicates the path originating at the reference host, $\overline{v_0}$, traversing nodes $\overline{v_1}$ through $\overline{v_{k-1}}$ and terminating at $\overline{v_k}$. As a shorthand, we introduce the notation, P_n to indicate the piece of the path, P, from $\overline{v_0}$ to $\overline{v_n}$, where $\overline{v_n}$ is one of the nodes along the path. Using this notation, $P_k = P$.

Given a path in $\overline{G}$, the topological cost of the path from the reference node, $\overline{v_0}$, to a host, $\overline{v_k}$, can be defined recursively using the path cost function, *Cost*, specified by the reference host's application. The cost of the path from the reference host, $\overline{v_0}$, to node $\overline{v_k}$ along a particular path, P_k, is represented by $f_{v_0}(P_k)$. The recursive evaluation to determine this value is:

$$f_{v_0}(P_k) = Cost(f_{v_0}(P_{k-1}), w_{k-1,k}) \tag{1}$$

$$f_{v_0}(\langle \overline{v_0} \rangle) = 0 \tag{2}$$

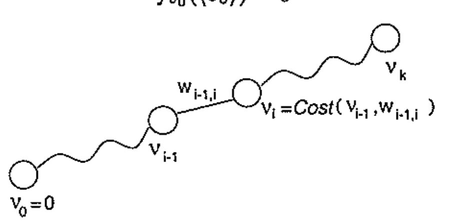


Figure 3: The recursive cost function

Figure 3 shows the recursive cost function. The figure shows that the cost of, or distance to, host $\overline{v_i}$, represented by ν_i, results from the evaluation of the application specified cost function over the weight of edge $\overline{e_{i-1,i}}$ and the cost of, or distance to, host $\overline{v_{i-1}}$.

The family on vacation would like the path cost function to reflect the physical distance from their car to other communicating nodes. We will see at the end of this section how we mathematically define a cost function to accomplish this. It is more complicated than it first appears because of the requirement that the cost of a path be strictly increasing as the number of hops from the reference grows. We do provide two other cost functions here.

We first revisi the network hop count example. Assume that the weight of a link is one. Then this example intends that the cost of a path be the number of hops along that path. Therefore, the associated cost function should be additive. In this case,

$$f_{v_0}(P_k) = f_{v_0}(P_{k-1}) + w_{k-1,k}$$

While useful, the hop count example is a bit too simplistic. Here we introduce a second example that we will carry through the explanations. Using bandwidth as a measure of cost should indicate that a path that traverses a link of lower bandwidth costs more (i.e., takes longer to send the same data) than a path with higher bandwidth links. For this example to conform to the requirement that the cost of a path strictly increases as the distance from the reference host grows, we make the simplifying assumption that the bandwidth decreases as the number of hops increases. At the end of this section we will show a mechanism for accommodating a cost function of this type without these assumptions. Assume that the weight on a link is the inverse of the bandwidth; lower bandwidth links have higher weights. The reasoning behind this weight assignment will be explained later. Because the cost of the path should reflect the lowest bandwidth encountered on that path, the cost function for a particular node indicates the minimum bandwidth, or highest weight, on the path. In this case,

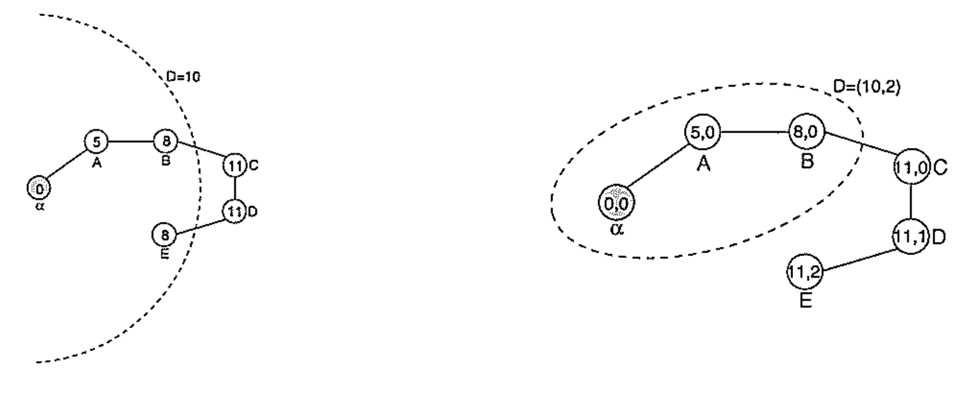
$$f_{v_0}(P_k) = \max(f_{v_0}(P_{k-1}), w_{k-1,k})$$

The cost of the path from the reference node to each reachable node can be defined using this path cost function. In a later section, we will see what the weights on the edges mean and how they are derived from the properties of the ad hoc network. Before we can define weights, however, we need to map the physical ad hoc network to an abstract space, a graph. The weights will then allow us to quantify the reference node's context, giving us the logical network, $\overline{G}$, over which the cost function has been defined.

3.4 The Physical Network

To begin the mapping of the ad hoc network to an abstract space, we represent the entire network as a graph, $G = (V, E)$, where mobile hosts are mapped to V, the graph's vertices, and the connections between hosts are mapped to E, the graph's edges. In the ad hoc network, every host and link has attributes that we intend to fold into a single weight on each edge in our abstract graph. To do this, we first map the host and link attributes to the abstract space represented by graph, G, by placing values on every vertex and edge. First, we quantify the properties of a mobile host as a value, ρ_i on the vertex $v_i \in V$ representing the mobile host in the graph. Formally, $\rho : V \to P$. The value of ρ_i can be a combination of a host's battery power, location, load, service availability, etc.

Second, we quantify the properties of a network link as a value, ω_{ij} on the edge $e_{ij} \in E$ representing the edge in the graph. Formally, $\omega : E \to \Omega$. The value of ω_{ij} can be a combination of the link's length, throughput, etc.



(a) (b)

$$f_{v_0}(P_k) = \begin{cases} (|f_{v_0}(P_{k-1}).V + w_{k-1,k}|, f_{v_0}(P_{k-1}).maxC, f_{v_0}(P_{k-1}).V + w_{k-1,k}, 0) & \text{if } |f_{v_0}(P_{k-1}).V + w_{k-1,k}| > f_{v_0}(P_{k-1}).maxD \\ (f_{v_0}(P_{k-1}).maxD, \max(f_{v_0}(P_{k-1}).maxD, c+1), f_{v_0}(P_{k-1}).V + w_{k-1,k}, c+1) & \text{otherwise} \end{cases}$$

(c)

Figure 4: (a) Physical distance only (b) Physical distance with hop count (c) The correct cost function

3.5 Logical View of the Network

Different properties of the physical network may interest different applications. Because each application individually specifies which properties of hosts and links to use in its context specification, each application has its own interpretation of the physical network. Each interpretation of the properties of the underlying physical network represents a logical view for the corresponding application. We designate an application's logical network $\overline{G} = (\overline{V}, \overline{E})$. This is the logical network on which the cost function was built previously. We use the information about the node and link properties to create a topological 'distance' between each pair of connected nodes in the logical network, $\overline{G}$. To do this, we combine the quantifications of node properties and link properties into only weights on edges in $\overline{G}$. Given an edge, $e_{ij} \in E$ from the original mapping, G, and the two nodes it connects, $v_i, v_j \in V$, the weights of the two nodes, ρ_i and ρ_j are combined with the weight of the edge, ω_{ij}, resulting in a single weight, w_{ij} on the edge $\overline{e_{ij}} \in \overline{E}$ in the logical network. No host, $\overline{v_i} \in \overline{V}$ in the logical network has a weight. Formally, this projection from the physical world to the virtual one can be represented as:

$$\Gamma : P \times P \times \Omega$$

or more specifically,

$$w_{ij} = \Gamma(\rho_i, \rho_j, \omega_{ij}).$$

The value of w_{ij} is defined only if nodes v_i and v_j are connected.

As an example of a weight assignment, we will first revisit the network hop count example. As discussed, the weight in this example can be measured simply by placing a weight of one on every edge. More formally, let ω_{ij} be one for every $e_{ij} \in E$ in the original graph. The value of ρ_i will not be used. Then the weight, w_{ij}, of an edge, $\overline{e_{ij}} \in \overline{E}$ in the logical network is: $w_{ij} = \omega_{ij} = 1$.

While this example can serve as a useful measure in a real network application, it does not demonstrate the power of the abstraction being provided. For the bandwidth example introduced in the previous section, the weight on an edge in the graph representing the logical network reflects the inverse of the bandwidth available between two nodes. Let ρ_i in the original graph, G, be the maximum bandwidth at which host i is capable of transmitting. Then the weight of an edge, $\overline{e_{ij}}$ in the logical network graph can be calculated as:

$$w_{ij} = \frac{1}{\min(\rho_i, \rho_j)} \text{ if } e_{ij} \in E$$

It is reasonable to use the inverse of the bandwidth because a connection with a higher bandwidth can be considered 'shorter', while one of lower bandwidth 'longer'.

For our vacation scenario, we will assign weights on edges to reflect the distance vectors between connected hosts. The next section describes the assignment of these weights and defines the cost function used by the vacationing family. It also serves as an example for overcoming the strictly increasing requirement on path costs while still using distance as a metric.

3.6 A Complete Example

As mentioned when the bandwidth example was introduced, the path cost function does not satisfy the requirement that the costs along a path be strictly increasing unless we assume that the bandwidth of the hops decreases as the number of hops from the reference grows. Because this is not a reasonable assumption, we now introduce a complete example that circumvents these assumptions by combining a metric similar to the bandwidth with hop count.

This new metric will satisfy the requirements of the vacationing family that wishes to perform queries over its changing environment as their car travels across the country. The family would like to know the locations of and information about points of interest within five miles. This requires that the calculated context be based on this physical distance between the family's car and other reachable hosts. For this example, the weight placed on edges in the logical network reflects the distance vector between connected nodes. That is, given two connected nodes, the weight on $\overline{e_{ij}}$ connecting them accounts for both the displacement and the direction of the displacement between the two nodes. Formally,

$$w_{ij} = \vec{\mathrm{IJ}}$$

Figure 4a shows an example network where specifying distance alone causes the cost function to not satisfy the requirement that the function be strictly increasing. The figure shows the shaded reference host, α, and the results of its specified cost function. The cost function shown in this figure simply assigns as the cost of a node the physical distance to the reference. The bound the application specified in this example is $D = 10$. Notice that nodes C and D are outside of the context, while E should be placed inside the context. When the cost of the path is strictly increasing, host C knows that no hosts farther on the path will qualify for context membership. In this example, this condition is not satisfied, however, and no limit can be placed on how long context building messages must be propagated.

To overcome this problem, the cost function will be based on both the distance vector and a hop count. The cost function's value, ν at a given node consists of four values:

$$\nu = (maxD, maxC, \mathrm{V}, c)$$

The first value, $maxD$, stores the maximum distance of any node seen on this path. This may or may not be the magnitude of the distance vector from the reference host to this host. The second value, $maxC$, keeps the maximum number of consecutive hops for which the value of the cost function remained the same at any point previously on the path. The next value, V, is the distance vector from the reference host to this host. We will show below how this vector is calculated. The final value, c, indicates the number of hops for which $maxD$ has not changed. This may be less than or equal to $maxC$.

Specifying a bound for this cost function requires specifying a bound on both $maxD$ and $maxC$. It is also important that we define the comparison function for this metric. A given bound has two values, and if a host's cost function values meet or exceed either of these values, the host is outside the bound. That is, a host is in the specified context only if both its $maxD$ and its $maxC$ are less than the values specified in the bound. It is important to notice that neither the value of $maxD$ nor the value of $maxC$ can ever decrease. Also, if one value remains constant for any period of time, the other is guaranteed to eventually increase. This observation allows us to treat this cost function as strictly increasing.

Figure 4c shows the cost function for this distance example. In the first case shown in the example, the new magnitude of the vector from the reference host to this host is larger than the current value of $maxD$. In this case, $maxD$ is reset to the magnitude of the vector from the reference to this host, $maxC$ remains the same, the distance vector to this host is stored, and c is reset to 0. In the second case, $maxD$ is the same for this node as the previous node. Here, $maxD$ remains the same, $maxC$ is set to be the maximum of its old value and the current c incremented by one, the distance vector to this host is stored, and c is incremented by one.

Figure 4b shows the same nodes as in Figure 4a. In this figure, however, the cost function from Figure 4c assigns the path costs shown. The application specified bound shown in Figure 4b is $D = (10, 2)$ where 10 is the bound on the maximum distance ($maxD$) and 2 is the bound on the maximum of the number of hops for which the maximum distance did not change ($maxC$). As the figure shows, because the cost function includes a hop count and is based on maximum distance instead of actual distance, node C can correctly determine that no host farther on the path will satisfy the context's membership requirements. The values shown on the nodes in the figure reflect the pair of values, $maxD$, $maxC$.

4. CONTEXT COMPUTATION

The protocol developed takes advantage of the fact that an application running on reference host, α, does not necessarily need to know which other hosts are part of the acquaintance list. Instead, the application needs to be guaranteed both that, if it sends a message to its acquaintance list, the message is received only by hosts belonging to the list and that all hosts belonging to the list receive the message. The protocol described builds a tree over the network corresponding to a given application's acquaintance list. By its nature, this tree defines a single route from the reference node to each other node in the acquaintance list. To send a message to the members of the acquaintance list, an application on the reference node needs only to broadcast the message over the tree.

4.1 Related Work

Creating paths between nodes in an ad hoc network is neither a new problem nor an easy one. Routing protocols for traditional wired networks do not function well in the ad hoc environment because of the many special conditions encountered in this new type of network. Hosts in ad hoc networks are constantly moving, and hosts that are encountered once are likely never to be encountered again. Ad hoc routing protocols can generally be divided into two categories. Table-driven protocols, such as Destination Sequenced Distance Vector (DSDV) routing [15] and Clusterhead Gateway Switch Routing [8] mimic traditional routing protocols because they maintain consistent up-to-date information for routes to all other nodes in the network [18]. This class of algorithms is based on modifications to the classical Bellman-Ford Routing algorithm [6]. Maintaining routes for every other node in the network can become quite costly. Performance comparisons [3] have shown that, while the overhead of DSDV is predictable, the protocol can be unreliable. Additionally, the overhead can be lessened by utilizing routing protocols from the second class, source initiated on-demand routing protocols. This type of routing creates routes only when requested by a particular source and maintains them only until they are no longer wanted. Ad-Hoc On-Demand Distance Vector (AODV) routing [16] builds on the DSDV algorithm but minimizes the routing overhead by creating routes on demand. Dynamic Source Routing (DSR) [11] requires that nodes maintain routes for source nodes of which they are aware in the system. Finally, the Temporally Ordered Routing Algorithm (TORA) [13] uses the concept of link reversal to present a loop-free and adaptive protocol. It is source initiated, provides multiple routes, and has the ability to localize control messages to a small set of nodes near the occurrence of a topological change. Another type of routing that relates well to our current work is Distributed Quality of Service Routing [5]. In this scheme, routes are chosen from the source to the destination based on the network resources available along that path.

While this is not an exhaustive survey of the current ad hoc routing protocols, it shows the diversity present among them. The main difference between the solutions offered by these protocols and the requirements of the acquaintance list problem previously described lies in the fact that each of the ad hoc routing protocols described requires a known source and a known destination. Instead, we would like a host to be able to specify abstractly the group of hosts with which to communicate.

Communication with a subset of the nodes in a network is accomplished using multicast routing protocols. One possible solution to our problem would build a multicast tree or mesh for the acquaintance list and then send messages over this structure. Multicasting in ad hoc networks has received much attention as of late. Early approaches used the shared tree paradigm commonly seen in wired networks. Shared tree protocols have been adapted for the wireless environment to account for mobility in these systems [9, 10]. More recent work in ad hoc multicasting has realized that maintaining a multicast tree in the face of a highly mobile environment can drastically increase the network overhead. These research directions have led to the development of shared mesh approaches in which the protocol builds a multicast mesh instead of a tree [2, 12]. Both the multicast tree and mesh protocols use a shared data structure approach. That is, they assume that for a given multicast group, there may be multiple senders. These senders share the tree built for the group to route their messages. While a shared approach might optimize a solution, an acquaintance list is built for a particular application running on a particular host. There is no need to create a shared data structure. Also, a sender is guaranteed that its messages will be received by all members of the multicast group, but these members initially registered with the group. While these protocols address the mobility that causes nodes to join and leave the group, the acquaintance list problem does not use a registration. Instead, a particular query should reach only the nodes that satisfy the context specification at the time of the query's life in the system.

In summary, our protocol will be influenced by the unicast and multicast protocols described above. We will need to address many of the same concerns as these protocols. Like them, our solution must account for the frequent mobility of the nodes, the transient nature of the connections, and the changing properties of both the nodes and the links in the network. Our approach, however, differs in some key aspects. First, a node does not necessarily know to which other nodes a particular query will be sent. Instead, the node can specify some properties of the path to the nodes with which it wants to communicate. Second, any data structure built over the system must guarantee that the path used to communicate with a node in an acquaintance list satisfies the constraint specified by the application. Finally, the protocol does not need to search the whole network for possible paths. As described in the previous section, the nature of the context specification guarantees that once a node that does not satisfy the specification is found, any nodes farther on that path will not satisfy the specification either. This last point is the key that guarantees that our protocol can reach a fixed point.

4.2 Protocol

As intimated in the introduction to this section, our protocol takes advantage of the fact that an application running on a reference host specifies the context over which it would like to operate, but the application does not need to know the identities of the other hosts in this context. Therefore, the context computation can operate in a purely distributed fashion, where responses to data queries are simply sent back along the path from whence they came. The protocol is also on-demand in that a shortest path tree is built only when a data query is sent from the reference node. Piggy-backed on this data message are the context specification and the information necessary for its computation.

Query, q	
$q.num$	the application sequence number of q
$q.s$	the sender of this copy of q NOT necessarily the reference node
$q.sd$	the distance from the reference to $q.s$
$q.d$	the distance from the reference to the host at which the query is arriving
$q.D$	the bound on the cost function
$q.Cost$	the cost function

Figure 5: The Components of a Query

Figure 5 shows the components of a query. Besides the components shown, each query also carries some data information for its corresponding application. The query's sequence number allows the protocol to determine whether or not this query is a duplicate. This prevents a particular host from responding to the same query multiple times.

It should be noted here that we will talk about a query's sender. This is not a term used interchangeably with the query's reference. The reference for a query is the host running the application for which the context is being constructed. The sender of a query is the most recent host on the path to this host.

The explanation of the protocol is divided into two sections: tree building and tree maintenance. After the presentation of the building of the shortest path tree, it will be easy to add the maintenance to the algorithm. Before we describe the algorithm itself, however, we present the information that a given host needs to remember about a given context specification.

State Information

Figure 6 shows the state variables that a host participating in a context computation must hold. This is the information for a host, β, that is part of α's acquaintance list. This shows only the information needed for participation in α's acquaintance list. In general, an individual host would be participating in multiple acquaintance lists and would therefore have a set of these variables for each such list.

Most of the state variables are self-explanatory. Two worth discussing are the sets C and I. C holds the list of all connected neighbors. Each of these neighbors has a link to it from this host; the weight of that link is stored in C and is referred to as w_c for some $c \in C$. This set is also used to store other paths to this host. If a host receives a

State	
id	this host's unique identifier
num	application sequence number initialized to -1
d	the distance from the reference node initialized to ∞
p	this host's parent in the tree
pd	parent's distance (or cost) from reference node
D	bound on the cost function
Cost	cost function
C	set of connected neighbors, the weight of the link to each, and the cost of the path to the neighbor. As a shorthand, we refer to the weight of a link to neighbor c as w_c and the cost of the path to c as d_c.
I	a subset of C containing the connected neighbors that are in the reference's context initially empty

Figure 6: State Variables

query from host c that would give it a cost $d_c < D$ that it does not use as its shortest path, it remembers c's cost, and associates it with c in C. When we discuss maintenance of the tree later, this information will prove useful in quickly finding a new shortest path to replace a defunct path. The set I contains all of the neighbors that this host knows are in the reference host's context. This host will use this information when we discuss later how to recover the memory used to store a context specification's state on a host.

Tree Building

The application is assumed to maintain the weights on the links in the network by updating them in response to changes in the contextual information important to that application. We also assume that the weights for the links have been calculated and that each host has been notified of the weights of the links connecting to it. For each of these links, a host should know both the weight of the link and the host on the other side of the link.

Any information that a particular host requires for computation of another host's context arrives in a query; there is no requirement for a host to keep any information about a global state. We assume that the topological changes in the network and the application's issuance of queries are atomic with respect to each other. We also assume that the queries are atomic with respect to each other, i.e., one query finishes completely before the application issues the next one.

Because the protocol services queries on-demand, it does not build the tree until a request is made. To do this most efficiently, the information for building and maintaining the tree is packaged with the application's data queries. An application with a data query ready to send bundles the context specification with the query and sends it to all its neighbors. When such a query arrives at a host in the ad hoc network, it brings with it the cost function and the bound which together define the context specification. It also brings the cost to this host.

The first query that arrives at a host is guaranteed to have a cost lower than the one already stored because the cost is initialized to ∞. Subsequent copies of the same query are disregarded unless they offer a lower cost path. As shown in the second **if** block of the QUERYARRIVES action in Figure 8, when a shorter cost path is found, the cost of the new path, the new parent, and the new parent's cost are all stored. Also, the query is propagated to non-parent neighbors whose distance will keep them inside the context specification's bound. This is done through the *PropagateQuery* function, described with the protocol's support functions in Figure 7. For each non-parent neighbor, c, this host applies the cost function to its own distance and the weight of the link to c. If this results in a cost less than the context specification's bound, D, the host propagates the query to c. A host must propagate a query with a lower cost even if its application has already processed it from a previous parent because this shorter path might allow additional downstream hosts to be included in the context.

When a host receives a query that it has not seen before (i.e., the sequence number of the arriving query is one more than the stored sequence number), the application automatically processes it regardless of whether or not it arrived on the currently stored shortest path. A host does not wait for new queries to come only from its parent because it is possible that the path through the parent no longer exists or that its cost has increased. If the path does still exist and is still the shortest path, the query will eventually arrive along that path, causing the cost to be updated and the effects to be propagated to the children. Upon receiving a new query, the host stores the cost of the query, the new parent, the new parent's cost, and the sequence number, then propagates the query in the manner described above. Finally, the host sends the data portion of the query to the application for processing using the *AppProcessQuery* support function described in Figure 7.

Actions

QUERYARRIVES(q)
  Effect:
    save information from q ($Cost := q.Cost, D := q.D$)
    update C ($d_{q.o} := q.sd$)
    if $q.num = num + 1$ **then**
      record information ($d := q.d, p := q.s, pd := q.sd$)
      Propagate Query(q)
      AppProcessQuery(q)
      save the sequence number ($num := q.num$)
    else if $q.d < d$ **then**
      record information ($d := q.d, p := q.s, pd := q.sd$)
      PropagateQuery(q)
    end

Figure 8: Context Computation

An application can perform two different types of operations: transient and persistent. A transient operation is a one-time query or instruction. For example, in the traditional children's card game, Go Fish, a player A's request "Do you have a six?" would represent a transient query. All other players, if they are part of the context, can easily respond "yes" or "no" and move on. In a modified version of the game, player A might request to be notified when another player finds a six. This is an example of a persistent query because the other players have to remember that another player asked for a six. As long as player A still wants a six, all players that enter the context have to be notified of the persistent query.

The family on vacation issues both transient and persistent opertions over its context of five miles. When the car needs gas, the family asks for the nearby gas stations. This is a transient operation. Because the family is vacationing, however, they would also like a list of nearby points of inter-

Support Functions	
PropagateQuery(q)	for each non-parent neighbor, c, send the query to c if $Cost(d, w_c) < D$ by calling SENDQUERY to c after setting $q.d = Cost(d, w_c)$ and $q.s = id$ in the query. Also updates I to include exactly those c to which the query was propagated
AppProcessQuery(q)	the application's processing of the data message part of the query
SendCleanUps	for each non-parent neighbor, c, send a clean up message to c if $Cost(d, w_c) \geq D$ by calling SENDCLEANUP to c
PropagateCleanUps	for every member of I, send a clean up message by calling SENDCLEANUP

Figure 7: Support Functions

est (e.g. museums, state parks, etc.) displayed in a list. To accomplish this, the system registers a persistent operation on the context of five miles. As the car moves across the highway, the list is updated to reflect the changing points of interest.

The protocol presented in Figure 8 is sufficient if the specifying application issues only transient operations over its context. In this case, the context needs to be recomputed only if a new query is issued. Because the protocol propagates each query to all neighbors of an included host, the shortest path will be computed each time, even if the weights of the links have changed between the queries.

For transient operations alone, the protocol essentially rebuilds the shortest path tree each time a query is issued, on-demand. For these purposes, the only state a host needs to remember for a given context specification is its own current shortest distance, its parent, and the sequence number. It uses its distance to compare against other potentially shorter paths and the identity of its parent to return messages to the reference along the current shortest path. The need for the remaining state variables in Figure 6 becomes clear when we introduce tree maintenance to the protocol. Because the protocol in Figure 8 does no maintenance on the tree, there is also no way for a host to recover the memory used by this context specification. We will see in the next section how adding tree maintenance allows us to clean up context specification storage and accommodate persistent queries.

Tree Maintenance

The tree requires maintenance whenever the topology of the ad hoc network changes. Any topology change that affects the current context specification directly reflects as a change in at least one link's weight. We assume that the underlying system brings such a change to the attention of both hosts connected by the link. That is, if weight, w_{ij} changes, then hosts v_i and v_j are both notified.

When an application needs to leave persistent operations on other hosts in its context, that context needs to be maintained, even when no new queries are issued over it. Hosts whose cost grows as a result of a network topology change should be removed from the acquaintance list, while hosts that enter the context after the persistent query has been issued should be notified of the query. To do this, the system needs to react to changes in weights on links and recalculate the shortest paths if necessary. Again, we assume that topology changes are atomic with respect to the application's operations. In the case of persistent operations, this means that the topology changes are atomic with respect to the registration and deregistration of the persistent operations and the transmission of the results of these operations.

Because both hosts connected by the link are notified of any change, both can take measures to recalculate the shortest path tree if necessary. Figure 9 shows the same protocol presented in Figure 8. A new action, WEIGHTCHANGEARRIVES has been added to deal with the dynamic topology. This action is activated when the notification of a weight change arrives at a host. The weight changes are divided into two categories: the weight of the link to the parent has changed, and any other weight has changed.

```
Actions

QUERYARRIVES(q)
   ... as before

WIEGHTCHANGEARRIVES(wnew_id)
   Effect:
      if id = p then
         calculate the cost (d := Cost(pd, wnew_id))
         if wnew_id > w_p then
            calculate shortest path not through p
                  (minpath := min_c Cost(d_c, w_c))
            if minpath < d then
               reset the cost (d := minpath)
               reset the parent
            end
         end
         set the query fields (q := <num, id, d, D, Cost>)
         PropagateQuery(q)
      else if wnew_id < w_id then
         if Cost(d_id, w_id) < d then
            recalculate cost (d := Cost(d_id, w_id))
            reset the parent (p := id)
            set the query fields (q := <num, id, d, D, Cost>)
            PropagateQuery(q)
         end
      end
      store the new weight (w_id := wnew_id)
```

Figure 9: Context Computation and Maintenance

In the first case, the path through the parent has either lengthened or shortened. If the length of the path through the parent has increased, then it is possible that the shortest path to this node from the reference node is through a different neighbor. The node sets its cost to be the minimum of the cost through the old parent and the shortest path through any other neighbor. To find the shortest path through a non-parent neighbor, the host accesses the information stored in the state variable, C. On the other hand, if the length of the path through the parent has shortened, the node should still be included in the context and the shortest path to it from the reference should still be through the same parent. In either case, the node recalculates its distance and propagates the information to its neighbors, using the support function, *PropagateQuery*. The neighbors will then process the weight change information using the already discussed QUERYARRIVES action.

If the weight change has occurred on a link to a non-parent

```
Actions

QUERYARRIVES(q)
  Effect:
    save information from q (Cost := q.Cost, D := q.D)
    update C (d_{q.o} := q.sd)
    if q.num = num + 1 then
      record information (d := q.d, p := q.s, pd := q.sd)
      PropagateQuery(q)
      AppProcessQuery(q)
      save the sequence number (num := q.num)
      SendCleanUps
    else if Cost(q.d, w_{q.s}) < d then
      record information (d := q.d, p := q.s, pd := q.sd)
      PropagateQuery(q)
    end

CLEANUPARRIVES(id)
  Effect:
    if id = p then
      calculate shortest path not through p
            (minpath := min_c Cost(d_c, w_c))
      if minpath < D then
        reset the cost (d := minpath)
        reset the parent
        set the query fields (q := ⟨num, id, d, D, Cost⟩)
        PropagateQuery(q)
        SendCleanUps
      else
        PropagateCleanUps
        clean up local memory
      end
    else
      update d_{id} in C
    end

WIEGHTCHANGEARRIVES(wnew_{id})
  Effect:
    if id = p then
      calculate the cost (d := Cost(pd, wnew_{id}))
      if wnew_{id} > w_p then
        calculate shortest path not through p
              (minpath := min_c Cost(d_c, w_c))
        if minpath < d then
          reset the cost (d := minpath)
          reset the parent
        end
      end
      if d < D then
        set the query fields (q := ⟨num, id, d, D, Cost⟩)
        PropagateQuery(q)
        SendCleanUps
      else
        PropagateCleanUps
        clean up local memory
      end
    else if wnew_{id} < w_{id} then
      if Cost(d_{id}, w_{id}) < d then
        recalculate cost (d := Cost(d_{id}, w_{id}))
        reset the parent (p := id)
        set the query fields (q := ⟨num, id, d, D, Cost⟩)
        PropagateQuery(q)
      end
    end
    store the new weight (w_{id} := wnew_{id})
```

Figure 10: Context Computation and Maintenance with Clean Up Mechanism

neighbor, then the change interests this host only if it causes the path through the neighbor to be shorter than the path through the parent. For this to be the case, the link's weight must have decreased. Because this host is storing distance information for all of its neighbors, however, it can simply calculate what the new distance would be, compare it to the stored cost, and reset its values if they have changed. If these calculations change the cost to the node, it should package the current context values in a query and propagate that query using the *PropagateQuery* support function.

The protocol presented in Figure 9 still does not free the memory used to store information about the reference host's context specification. As a car moves across the country, it leaves information about its specified context on every host it encounters. The car may never come back, so each host that was part of the context would like to recover its memory when it is no longer part of the context specified. We can build a clean up mechanism into the protocol as shown in Figure 10. Whenever it is possible that a change has pushed a host that was in the context out of the context, the parent should notify the child that its context information is no longer useful and should be deleted. There are two places in the algorithm where a change might push another node out of the context. The first is when a weight changes and the path through the parent becomes longer. Not only might this node be pushed out of the context, any of its descendants in the tree might also be pushed out. First, after calculating its new cost, the node should verify that it is still within the bound, D. If not, it should clean up its own storage. If this node is still within the bound, it propagates a copy of the current query to its neighbors that will remain within the bound and sends a message to the neighbors that are not within the bound instructing them to clean up this context specification's information if they know about it.

The other change required to the protocol occurs in the QUERYARRIVES action. When a query arrives with a new sequence number, it is possible that the shortest path has increased in cost, thereby pushing neighbors out of the context. To account for this, after propagating the query to all neighbors within the bound, D, the host should also send a clean up message to all neighbors not within D.

A new action, CLEANUPARRIVES has been added to the protocol shown in Figure 10 to deal with the arrival of the clean up messages. If the clean up message comes from the parent, it is an indication that there no longer exists a path to the reference that satisfies the context specification's constraints. In this case, a new shortest path is selected using the information in C and the information propagated. If no qualifying shortest path exists, the local memory is recovered. In both cases some clean up messages are sent. If the clean up message comes from a node other than the parent, the state variable C needs to be updated to reflect that the cost to the source is ∞.

5. DISCUSSION

The abstraction allowed by the context specification is quite powerful. Through use of diverse examples, we have provided a glimpse of its expressive power. This power comes from the abstraction's ability to accomodate any property of a network that can be quantified either on an individual host or on the link between two connected hosts. In this way, the abstraction itself does not limit the definition of context but leaves it open to the application's needs. The context can be computed not just over neighboring nodes, but over all reachable nodes in the ad hoc network. Because ad hoc networks can grow very large, the application developer or user must specify reasonable contexts that can be computed and operated over efficiently. Specifying a wider context might be desirable for applications that operate in a more static environment or can sacrifice performance. A narrower context might be desirable for applications operating in a highly dynamic or densly poplulated environment.

The protocol presented in the previous section offers one example of a distributed implementation of the context computation. This protocol makes some assumptions about atomicity guarantees of both the computation of the context and the operation over the context. One requirement is that the queries issued by the reference application are atomic with respect to each other. That is, it must be guaranteed that a query finishes before a subsequent query is issued. This guarantee is not built into the protocol but could be easily added in a number of ways. The application could compute a timeout over network properties after which it should be guaranteed that the query has propagated along the entire shortest path tree. On the other hand, the protocol might require that every member of the context reply to the reference host with a list of its "children". When all descendants have responded the application is free to issue a new query.

6. CONCLUSION

The ideas behind this work are rooted in the notion that mobile application development could be simplified if the maintenance of contextual information were to be delegated to the software support infrastructure without loss of flexibility and generality. This paper demonstrates the feasibility of such an approach and outlines a novel technical solution for context specification. The notion of context is broadened to include, in principle, the entire ad hoc network, yet it can be conveniently limited in scope to a neighborhood whose size and scope is determined by the specific needs of each application as they change over time.

To ensure the atomicity of an application's operations, we make assumptions about the atomicity of network topology changes and their propagation through the network for rebuilding the context. Future work will explore ways to relax these assumptions by weakening the required guarantees on both context maintenance and the operations performed on that context.

Acknowledgements

This research was supported in part by the National Science Foundation under Grant No. CCR-9970939. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation.

7. REFERENCES

[1] G. Abowd, C. Atkeson, J. Hong, S. Long, R. Kooper, and M. Pinkerton. Cyberguide: A mobile context-aware tour guide. *ACM Wireless Networks*, 3:421–433, 1997.

[2] S. Bae, S.-J. Lee, W. Su, and M. Gerla. The design, implementation, and performance evaluation of the On-Demand Multicast Routing Protocol in multihop wireless networks. *IEEE Network, Special Issue on Multicasting Empowering the Next Generation Internet*, 14(1):70–77, January/February 2000.

[3] J. Broch, D. Maltz, D. Johnson, Y.-C. Hu, and J. Jetcheva. A performance comparison of multi-hop wireless ad hoc network routing protocols. In *Proceedings of the ACM/IEEE MobiCom*, pages 85–97, October 1998.

[4] G. Chen and D. Kotz. A survey of context-aware mobile computing research. Technical Report TR2000-381, Department of Computer Science, Dartmouth College, November 2000.

[5] S. Chen and K. Nahrstedt. Distributed quality-of-service routing in ad-hoc networks. *IEEE Journal on Selected Areas in Communications*, 17(8):2580–2592, August 1999.

[6] C. Cheng, R. Riley, and S. Kumar. A loop-free extended Bellman-Ford routing protocol without bouncing effect. In *Proceedings of the ACM SIGCOMM*, pages 224–236, 1989.

[7] K. Cheverst, N. Davies, K. Mitchell, A. Friday, and C. Efstratiou. Experiences of developing and deploying a context-aware tourist guide: The GUIDE project. In *Proceedings of MobiCom*, pages 20–31. ACM Press, 2000.

[8] C. Chiang and M. Gerla. Routing and multicast in multihop, mobile wireless networks. In *Proceedings of IEEE International Conference on Universal Personal Communications*, pages 546–551, October 1997.

[9] C. Chiang, M. Gerla, and L. Zhang. Adaptive shared tree multicast in mobile wireless networks. In *Proceedings of GLOBECOM '98*, pages 1817–1822, November 1998.

[10] S. Gupta and P. Srimani. An adaptive protocol for reliable multicast in mobile multi-hop radio networks. In *IEEE Workshop on Mobile Computing Systems and Applications*, pages 111–122, 1999.

[11] D. Johnson and D. Maltz. Dynamic Source Routing in ad hoc wireless networks. In Imielinski and Korth, editors, *Mobile Computing*, volume 353. Kluwer Academic Publishers, 1996.

[12] E. Madruga and J. Garcia-Luna-Aceves. Scalable multicasting: The core assisted mesh protocol. *ACM/Baltzer Mobile Networks and Applications, Special Issue on Management of Mobility*, 1999.

[13] V. Park and M. Corson. A highly adaptive distributed routing algorithm for mobile wireless networks. *IEEE Infocom*, 1997.

[14] J. Pascoe. Adding generic contextual capabilities to wearable computers. In *Proceedings of the 2nd International Symposium on Wearable Computers*, pages 92–99, October 1998.

[15] C. Perkins and P. Bhagwat. Highly dynamic Destination-Sequenced Distance-Vector routing (DSDV) for mobile computers. In *ACM SIGCOMM '94 Conference on Communications Architectures, Protocols and Applications*, pages 234–244, October 1994.

[16] C. Perkins and E. Royer. Ad-hoc On-demand Distance Vector routing. In *Proceedings of the 2nd IEEE Workshop on Mobile Computing Systems and Applications*, pages 90–100, February 1999.

[17] B. Rhodes. The wearable remembrance agent: A system for augmented memory. In *Proceedings of the 1st International Symposium on Wearable Computers*, pages 123–128, October 1997.

[18] E. Royer and C.-K. Toh. A review of current routing protocols for ad hoc mobile wireless networks. *IEEE Personal Communications*, pages 46–55, April 1999.

[19] D. Salber, A. Dey, and G. Abowd. The Context Toolkit: Aiding the development of context-enabled applications. In *Proceedings of CHI'99*, pages 434–441, 1999.

[20] R. Want et al. An overview of the PARCTab ubiquitous computing environment. *IEEE Personal Communications*, 2(6):28–33, December 1995.

[21] R. Want, A. Hopper, V. Falco, and J. Gibbons. The Active Badge location system. *ACM Transactions on Information Systems*, 10(1):91–102, January 1992.