Context-Aware Routing in Wireless Mesh Networks

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ABSTRACT

Wireless mesh networks promise to deliver resilient connectivity among network nodes, allowing data to be relayed seamlessly between mobile clients and infrastructure. Routing is the vital process in archiving self-configuration, self-healing and, to some degree, self-optimization. However, the heterogeneity of network nodes and highly dynamic network topologies create new challenges for developing efficient and adaptive routing solutions. The increasing amount and complexity of information that routing solutions have to consider, in order to cope with the changing network situation and/or user requirements, is a key challenge. We propose adopting a reconfigurable context management system to simplify the task of accessing a variety of information required by adaptive routing protocols and to hide the low-level complexities of information sources management. In addition, we show how our middleware supports fault-tolerance of various information failures, freeing protocol developers to concentrate on improving the routing mechanism and the metric information model of routing.

General Terms

Context-Aware Routing

Keywords

Context-Aware, Routing, Wireless Mesh Networks

1. INTRODUCTION

Wireless Mesh Networks (WMNs) [1] have demostrated their potential in a variety of application domains, from community networks to public safety and crisis management [16]. A WMN can be classified as a client, infrastructure or hybrid mesh. In the latter case, both mobile client devices and infrastructure nodes (mesh routers) provide routing and forwarding functionality. WMNs are intended to be self-organizing, possessing *self-configuring*, *self-healing* and some degrees of *self-optimizing* abilities, which are the cornerstones of the autonomic computing paradigm [13]. Earlier solutions [1, 5, 18, 19, 20] used *multi-hop*, *multi-channel*, *multi-path* and *multi-radio* approaches to address specific challenges in WMNs: (i) to enlarge network coverage; (ii) to minimize radio interference; (iii) to maximize network capacity; and (iv) to improve network reliability. Routing protocols play a vital role in managing the formation, configuration and maintenance of the topology of the network, while routing metrics, which the protocols define, are responsible for determining the creation of paths in the network.

In the process of discovering *optimal* paths from source to destination nodes, a variety of information is exploited, evaluated and considered by the routing metrics to generate estimated *weights* for possible alternative routes in the network. Information regarding network nodes (type, hop count), radio interfaces (transmission range, channel) and/or medium of transmission (Signal-Noise-Ratio, interference) is commonly considered in existing routing protocols [20]. These parameters are carefully selected, gathered, evaluated and added to the protocols (normally *hard-wired* in implementation) in order to achieve optimal configuration under specific conditions. However, there are several problems with this approach. First, *hard-wiring* of parameters directly into the route selection process is not a flexible approach as it is difficult or impossible to introduce new parameters after the protocol is designed and deployed; second, sources of information are normally prone to various failures (e.g., disconnection, physical damage), so routing protocols must provide mechanisms to withstand these failures and to reconfigure the failed sources where possible; furthermore, information gathered from heterogenous information sources can be ambiguous and erratic, which means routing protocols must verify the correctness of information and/or ensure an acceptable quality of this information.

WMNs are increasingly deployed in hazardous and highly

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dynamic scenarios, such as fire-fighting, where a wide range of environmental factors have a substantial influence over network performance (such as the impact of fire and high temperature on signal propagation in different frequency bands). By tapping into this environmental information using heterogeneous information sources (e.g., sensors of varying types), routing protocols can potentially dynamically adapt to changing situations, thereby improving reliability, robustness and real capacity. We draw upon research from the field of context-aware computing, in which applications adapt to the changing environment, as a promising way to address these challenges.

In context-aware computing, applications use information gleaned from the environment and users (termed *context information*) to adapt their behavior to changes in the computing environment or user circumstances. Routing in WMNs can be treated as a context-aware application, which is required to adapt to changes in the network topology, node status and/or external interference. A variety of context information reflecting these changes can be applied to routing protocols to improve network performance. One example that lends credence to the treatment of routing as a context-aware application is the use of knowledge about node mobility to dynamically adjust the time out parameter (indicates how long a route stays valid) of a route in the routing table to minimize the number of route discovery requests in protocols such as AODV [17].

In this paper, we explore various challenges in developing effective and adaptive routing protocols for WMNs and propose a model- and standards-based architectural approach to address the challenges of accessing a variety of information and managing heterogenous information sources. We argue that the use of a context management system will offer a high-level and easy-to-use information abstraction layer for experimenting, prototyping and developing adaptive routing protocols and metrics.

The rest of this paper is organized as follows: Section 2 gives an overview of routing in WMNs and discusses the needs of adaptive routing. An overview of our autonomic context management system (ACoMS) will be discussed in Section 3. In Section 4, we illustrate our approach to support context-aware routing with existing routing metrics and one example hybrid metric, which is followed by a qualitative evaluation and discussion in Section 5. Section 6 discusses current approaches to support context-aware routing. Finally, we conclude the paper and discuss our plan for future work.

2. ROUTING

Developing efficient and robust routing protocols for WMNs has been a research challenge for many years due to the heterogeneity of network nodes and the dynamic nature of network topologies. Essentially, routing is the process of selecting paths between sources and destinations through an arbitrary number of intermediary nodes in a network to allow the establishment of high-level application communication. The routing protocol can determine the paths by assigning a *cost/weight* to each potential path from the source to the destination, where the weights are computed using one or more routing metrics, and then select the lowest cost path. Therefore, routing consists of two fundamental components: *routing protocols* and *routing metrics*.

Routing Protocols manage the formation, configuration and maintenance of the topology of a network; in other words, they define the mechanism of how routes should be created, maintained and updated. Routing protocols for WMNs can be categorized into two types [20] : *proactive routing*, in which every node in the network maintains one or more tables of routing information to other network nodes and consistently keeps an up-to-date view of the whole network; and *reactive routing*, whereby the paths from source nodes to destination nodes will be created only when there are requests for transmission/forwarding of packets from the sources.

	Global	Link	Local: Interface	Local: Node
Static			InterfaceType	NodeType PowerSource
Dynamic	HopCount* Topology	LinkQuality* LinkCapacity* (Bandwidth) LinkLoad Delivery/Loss Ratio Channel NoiseLevel	LinkCongestion* RetransmissionCnt* TransmissionCost Channel	PowerLevel* NodeStatus Mobility TrustLevel GeoLocation

* commonly used metric information

Figure 1: Classification of Example Metric Information

Routing Metrics are a vital factor in determining the efficiency and robustness of the routing protocols, since they are the element computing the weight of a particular route using relevant parameters. For this reason, the paper focuses on the problems of gathering parameter values in current routing metrics design.

A number of routing metrics have been proposed and studied, they include: Hop Count, ETX [3], ETT [5], WCETT [5], MIC [20] and iAware [19]. In general, the evolution of routing metrics from ETX to iAware has been achieved by adding extra parameters (or *metric information*) to the predecessor, with each new parameter capturing some additional aspect of bandwidth, neighboring channels or external interference. Figure 1 shows a classification of example metric information adopted by current routing protocols. *HopCount*, *LinkCongestion*, *LinkQuality*, *LinkCapacity* and *RetransmissionCnt* are traditional parameters incorporated in many existing metrics. This information is generally simple to obtain from network nodes or packet headers. In contrast, higher level information, such as *PowerLevel*, *Mobility* and *TransmissionCost*, are receiving more attention in modern routing protocols [6, 12, 15]. The more information a routing metric considers the more complete is its understanding of the network and external factors; it follows, therefore, that the routing protocol is better able to support adaptive routing. However, in current approaches, this higher level information is usually complex and prone to various failures, incurs greater processing costs, and increases code complexity in the protocols making convergence, maintenance and simplicity requirements harder to guarantee.

In this paper, we show how an information abstraction layer, in the form of a context management system, can simplify access to a variety of information sources and mediate the complexities of information source discovery, management and reconfiguration. The decoupled information layer

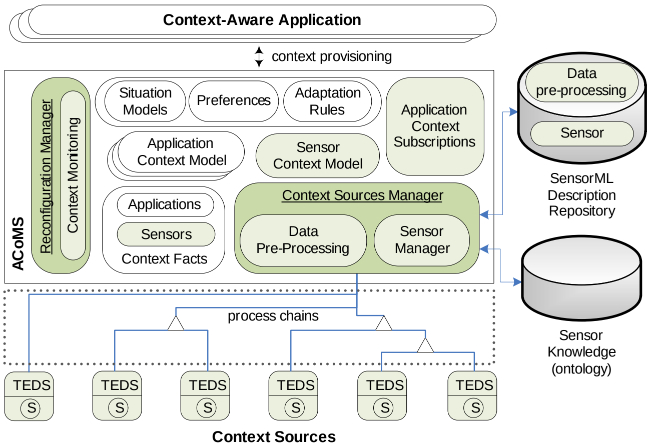

Figure 2: Open Context-Aware System Architecture

will also provide a modular architecture and encourage reuse of components for resource management as well as data pre-processing models, so that the functions of monitoring and reconfiguring the information gathering and pre-processing tasks is provided by this abstraction layer rather than individual routing protocols. This approach frees protocol designers from concerns about low-level information access complexities and allows them to concentrate on the actual routing mechanism or the design of the routing metric.

3. AUTONOMIC CONTEXT MANAGEMENT SYSTEM

To achieve the goal of simplifying access to a variety of information and mediating complexities in low-level information gathering, processing, management and dissemination, we propose the use of our autonomic context management system - ACoMS. Figure 2 illustrates the architecture of context-aware systems consisting of context-aware applications (various routing protocols), context information sources (sensors, probing services) and ACoMS. The ACoMS middleware processes, manages and evaluates information gathered from heterogenous context sources, and makes this information available to high-level applications; in this case, they are the routing protocols with different routing metrics. In this paper, only the components of ACoMS necessary for supporting context-aware routing are explained in depth. Further information about ACoMS can be found in our other paper [10].

The Context Models capture the relevant concepts and relations required by context-aware applications - they abstract raw data gathered from the sources of context information (e.g., sensors, probing services). Such raw data may need to be pre-processed to acquire the form defined by the context model. If run-time replacement of a context information source is needed or the sources of context information are to be dynamically configured/activated when the applications start then a mapping is created from the context model to the appropriate source of raw context data. This raw data, possibly after being pre-processed, should provide the required higher level context information and associated metadata. We adopted our own *fact-based* context modeling approach [8, 9], which defines not only the types of context information required by the application, but also its metadata. This metadata includes the classification of information types into sensed, static, user-provided, and derived types, and Quality of Information (QoI). Informed by these context models, ACoMS maintains appropriate sources of information and pre-processes information into the representation the applications (the routing protocol in our case) require.

The Application Context Subscription Manager manages a collection of subscriptions that detail the type of context information required by the applications in addition to QoI and Quality of Service (QoS) constraints (including the frequency and granularity of information the applications need and some further constraints). Taken together, these application subscriptions inform ACoMS about the context provisioning and monitoring strategies it should employ.

The Context Source Manager manages low-level communications with context sources, and provides context source discovery, registration and configuration services. Context sources (physical or virtual) are self-describing with regard to their identification, characteristics and capabilities through the use of SensorML[1] descriptions or Transducer Electronic Data Sheet (TEDS) (an element of the IEEE 1451 standards family[2]) in the case of resource poor context sources [11]. When sources describe themselves using TEDS, ACoMS translates the TEDS description to SensorML. The context source manager pre-processes raw context data to high-level context information facts through a chain of dynamically assigned and standards-based process models [10]. The use of two well-defined and increasingly well-accepted sensor description standards in ACoMS enhances the overall interoperability of the system.

The Adaptation Manager stores higher-level context abstractions called *situations*, which are often a more appropriate representation for applications to use than context facts, along with preferences and triggering rules for individual applications [8]. The adaptation rules are triggered when specified situations are entered or exited (or possibly entered or exited). Situations, preferences and triggering rules provide a powerful and flexible approach to adaptation in applications. These elements are discussed in greater detail in the next section.

The Reconfiguration Manager performs cross-layer context monitoring throughout the system and reorganizes, in co-ordination with the Context Source Manager, the mappings between context fact types in the context models and appropriate sources. This is the component in ACoMS that delivers its self-healing capabilities.

4. CONTEXT-AWARE ROUTING IN WMNS

We now discuss how ACoMS, with reference to the elements described above, can support adaptive and context-aware routing. To retain focus on the overall goals of our proposal, we limit our example to a simple context model and associated situations and preferences.

4.1 Context Model

Figure 3 (a) shows the context models for three representative routing metrics:

[1] http://vast.nsstc.uah.edu/SensorML/
[2] http://ieee1451.nist.gov/

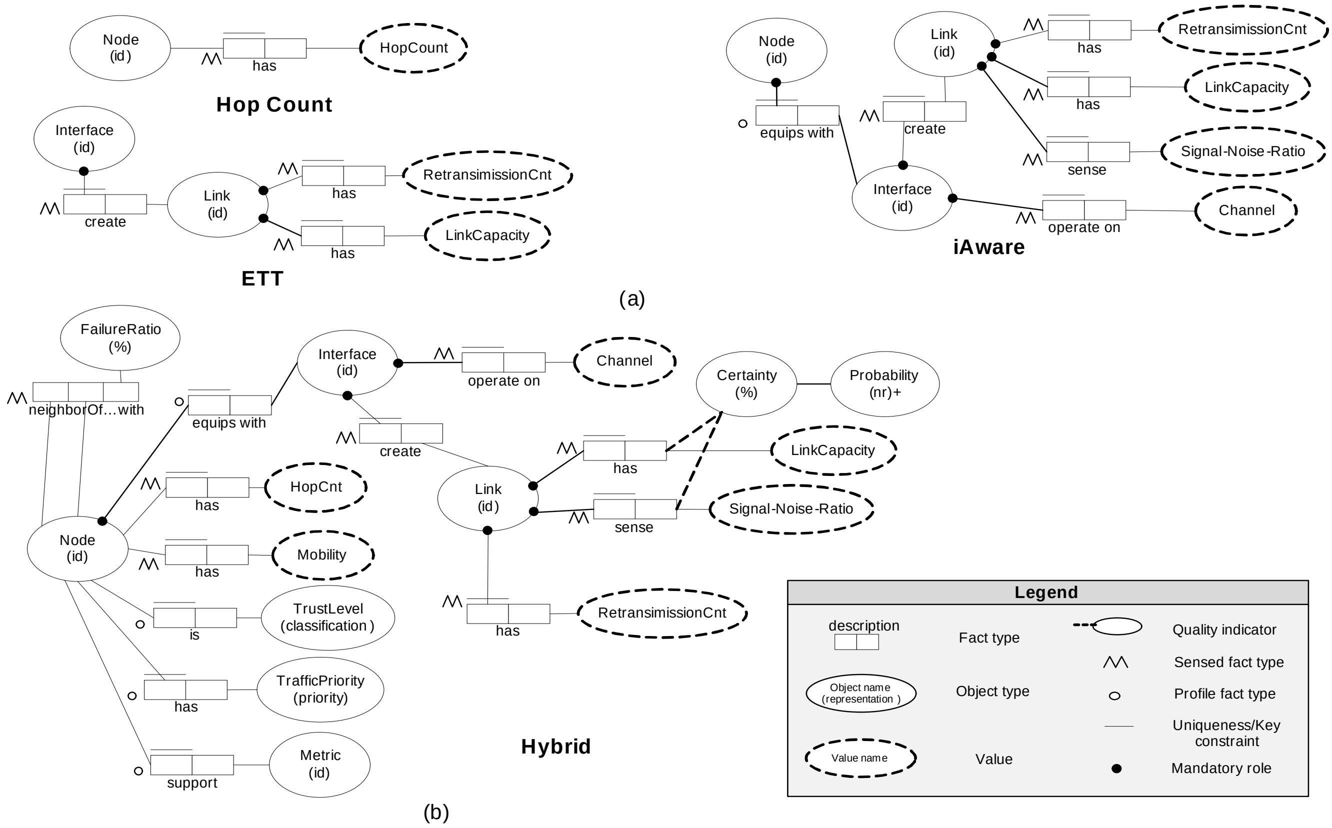

Figure 3: Context Models of Routing Metrics: (a) context models of existing routing metrics; (b) a *simplified* context model of a hybrid metric for context-aware routing.

- **HopCount** measures the number of hops between the source and destination nodes.

- **ETT** [5] is based on ETX [3], which is a link quality metric that considers the number of re-transimission required for a successful delivery of a frame over the wireless links. ETT augment ETX by taking into account differences in the link rate and capacity. It is defined as follows:

$$ETT = ETX \times \frac{S}{B}$$

  where S denotes the average size of a packet and B is the current link bandwidth.

- **iAware** [19] is an advanced metric, which incorporates a relatively complex interference model. For a path p, iAware is defined as follows:

$$iAware(p) = (1 - \alpha) \times \sum_{i=1}^{n} iAware_i + \alpha \times \max_{1 \leqslant i \leqslant k} X_j$$

  where the component X_j is the sum of the ETT [5] value of links that are on channel j in a system that has k orthogonal channels and α is a $0 \leqslant \alpha \leqslant 1$ tunable parameter, while the $iAware_i$ value is calculated by the combination of ETT value, Signal to Interference Noise Ratio (SINR) and Signal to Noise Ratio (SNR) [19].

The context models shown in Figure 3 (a) capture information relevant to these existing routing metrics. These models indicate the characteristics of the metric parameters and how these parameters relate to each other. For example, the radio interfaces attached to a node are modeled as *profiled*, while the parameters gleaned from the radio interface are *sensed*. Profiled information is user-supplied, and can be assumed to be initially very reliable; but profiled information often becomes out of date. Sensed context information is usually highly dynamic and prone to noise and sensing errors. The classification of information types allows context information to be managed and processed according to the characteristics of its type.

The hybrid context model, shown as an example, in Figure 3 (b) merges the models shown in Figure 3 (a) and captures some additional higher level parameters such as Mobility, TrustLevel and TrafficPriority. This model enables us to choose between the metrics described above, depending on the availability and quality of different parameter values. The hybrid model annotates the *LinkCapacity* and *Signal-Noise-Ratio* with QoI metadata to indicate, in this case, the *Certainty* of the information. This selection of a particular metric is made via the application of our preference model, described in detail below.

4.2 Preferences

By using Henricksen's and Indulska's preference model [8] in ACoMS, the *hard-wiring* approach used in most current routing protocols can be abandoned in favour of a more flexible alternative. Our solution allows developers, administrators and (when appropriate) users to define preferences which assign scores to the available routing metrics. The scores range from 0 to 1, or are one of the following special values: *veto* ($\natural$), *indifference* ($\perp$), *obligation* ($\overline{\wedge}$) or *undefined* (?). Usually, preferences are combined into preference sets, which can be merged upon evaluation using an aggregation function such as *average* and *weighted-average*. In this fashion, arbitrarily sophisticated preferences can be defined. We show three possible preference rules that select an appropriate routing metric taking into account the availability and evaluation of context information. They are defined as follows:

$$
\begin{aligned}
&\mathit{p1} = \\
&\quad \texttt{when } usesHopCount(n) \wedge highMobility(n, ngb) \\
&\quad \texttt{rate } 0.9 \\
&\mathit{p2} = \\
&\quad \texttt{when } usesETT(n) \wedge lowMobility(n, ngb) \\
&\quad \wedge Important(priority) \\
&\quad \texttt{rate } 0.7 \\
&\mathit{p3} = \\
&\quad \texttt{when } usesETT(n) \wedge highMobility(n, ngb) \\
&\quad \wedge \neg Important(priority) \\
&\quad \texttt{rate } \natural
\end{aligned}
$$

where n and ngb are network nodes and their neighbors correspondingly. These example preferences assign scores to metrics based on the mobility level of the network. Draves et al [4] show that the *HopCount* metric out-performs other more advanced metrics in highly dynamic network. This is encoded as a preference in the form of rule *p1*, which assigns a score of 0.9 to the *HopCount* metric when the network topology is changing frequently. The ETT metric, on the other hand, can be applied when the network is relatively static and reliability of packet delivery is required. Rule *p2* assigns a score of 0.7 to the ETT metric in less dynamic scenarios. Finally, rule *p3* shows an example in which the ETT metric is vetoed to exclude its use in highly mobile circumstances.

The elements for defining these preferences are *situations*. They represent higher level or abstract context by combining basic context facts conform to the context models in Figure 3. Several *situations* can be defined for our approach, but two of which are shown, as examples, below:

$$
\begin{aligned}
&usesETT(n): \\
&\qquad \exists m \bullet NodeSupports[n, m] \bullet \\
&\qquad m = \text{"}ETT\text{"} \\
&highMobility(n, ngb): \\
&\qquad \exists ratio \bullet NeighborOf[n, ngb, ratio] \bullet \\
&\qquad ratio = \text{"}high\text{"}
\end{aligned}
$$

For a node n, *usesETT(n)* holds true when this node supports the ETT metric, while the latter definition states that nodes have high mobility if their neighbor list is changing rapidly.

By adopting the situation abstractions as well as preference models, protocol developers can easily express rules to dynamically change the behavior of the protocols without the need to modify the protocol implementation.

5. DISCUSSION

The primary proposal made in this paper is to view routing in WMNs as a context-aware application that retrieves relevant context information from the context manager synchronously or asynchronously (i.e., via notifications). In this section, we will discuss the advantages of using a context management approach in adaptive routing for WMNs. We focus specifically on the application of our own reconfigurable context management middleware, ACoMS, to the problem of routing.

5.1 Ease of Information Access

ACoMS was designed as an information abstraction layer with autonomic characteristics (self-configuring, self-healing and self-optimizing) for multiple context-aware applications. It is responsible for discovering, configuring and managing sources of information in the manner discussed earlier, and for gathering, pre-processing and evaluating raw sensor data conforming to the context models. Moving these responsibilities to a middleware layer relieves the individual applications from having to perform these duties, and often results in smaller and simpler applications. This also means that development time can be significantly reduced. Each of these advantages apply to our context-aware routing proposal, in which hard-coding of metrics and specific access mechanisms for different information sources is replaced by a generic access mechanism from the perspective of the routing protocol.

5.2 Modular Architecture

The abstraction of information sources via a context management system greatly simplifies the task of adding new context sources and new types of context sources, since the mechanism by which the routing protocol accesses information is the same for all types of information (i.e., the routing protocol needs only to interface with the context manager, rather than separate information sources). This loose coupling means that reconfiguration of information sources at the middleware layer remains transparent to the routing protocols and enables more sophisticated solutions to be developed at each layer.

5.3 Rapid Prototyping

When the context manager is coupled with a preference model, as discussed earlier, it becomes possible to introduce new information types and modify the behaviour of the routing protocol without modifying a single line of source code of the routing protocol. Instead, when the context model is updated to reflect the addition of new kinds of information sources, only the preferences need to be modified, and these modifications can be made by administrators or users at runtime (i.e., without the need to reboot the router). One possibility that flows from this design is the ability to easily experiment with various information sources and metrics. The example shown in section 4.2 depicts only one possible combination of preferences for choosing an appropriate metric.

5.4 Adaptive Context Source Management

As adaptive routing protocols become more sophisticated, using information from an increasing number of local or remote sources, the need arises to dynamically reconfigure the sources of particular kinds of information. When routers are mobile, this is particularly true of information sourced remotely, or information sourced from sensors whose qualities change depending on the environment. For example, in a hybrid WMN, some nodes are configured as clients and others are configured as routers. By using location information, nodes could self-configure themselves as clients or routers. Over time, a router that notices it has not moved could configure itself as a mesh router, while a node that notices it moves constantly could configure itself as a mesh client. Note that to achieve this scenario, a node's neighbour list alone does not suffice to determine whether it is the local node that is mobile or the node's neighbours. Therefore, we need some other way of inferring mobility. One possibility is to use location information gathered from a locally attached GPS device and from the neighbouring nodes. GPS provides fairly high quality information in many outdoor environments, but performs poorly indoors and in outdoor environments surrounded by tall buildings or trees. Another source of location information is an indoor positioning system such as Cricket[3]. It is clear that the appropriate choice depends on the environment in which the router is deployed. A mobile router (which may be mobile in the absolute sense, but may not be mobile relative to other nodes in the network) may need to switch from one source of location information to another when the quality provided by the current source drops to an unsatisfactory level or when the source fails altogether.

ACoMS is developed specifically to cater to these dynamic circumstances, and performs the task of reconfiguring the sets of context sources when required. This process is hidden from the application.

5.5 QoS and QoI Guarantees

Based on the QoS and QoI requirements described in the context provisioning subscriptions, ACoMS allocates appropriate context sources for these context requests and preprocesses, if necessary, raw sensor data through a process chain defined in SensorML [11].

The appropriate allocation of context sources guarantees the system-level QoS by activating only required sources of information, this contributes to the overall optimization in lowering network traffic and resource usage and extending the operation life-time of the system when remote context sources are in use (as in temperature sensors that could provide forewarning of degraded link quality) . ACoMS also takes into account the QoI of each of the context sources, prioritising those context sources that can deliver higher quality information when composing a process chain and selecting context sources.

6. RELATED WORK

The existing approaches to context-aware routing fall into one of three broad categories: model-less, hard-coded solutions; modular abstraction architectures; and profile-based solutions. We give a brief overview of each of these approaches.

Dumitrescu and Guo [6] propose a context-assisted routing protocol for inter-vehicle wireless communication. Similar to other geo-location based routing approaches [12], location information is gathered from common location services (e.g., GPS) and exploited in the route computation process. In addition, some higher level context information is also considered in their approach, including: (i) the use of fixed road infrastructure to prevent topology holes along the paths; (ii) availability of fixed network infrastructures (roadside access points) to improve network performance and capacity; and (iii) current road traffic conditions to predict the load of the network. Mascolo and Musolesi [15] apply their SCAR algorithm to achieve adaptive routing in delay tolerant sensor networks. Their work is based on prediction of the future evolution of the system to select the best carriers for packet delivery. Using three types of context information - (i) degree of connectivity changes over a period of time between two nodes; (ii) co-location of nodes to their sinks; and (iii) battery level of the nodes - SCAR computes a delivery probability for each node in the network, and relays packets to nodes with higher estimated delivery probability along the paths toward the sinks.

These approaches are mainly focused on model-less and closed systems, which constrain them to small and simple networks. The required metric parameters are predetermined during development of the routing protocols; therefore to incorporate new information types and management modules for those information types, the protocols need to be reimplemented. The heterogenous and dynamic nature of WMNs demand more resilient and robust solutions. It is true that the aforementioned solutions can be modified accordingly to meet specific circumstances; however, the complexities created by the increasing amount of metric information and deployment in a range of environments will eventually overwhelm these approaches.

More modular architectures have been proposed by Battenfeld et al. [2] and Kohler et al. [14]. They aim to create loosely coupled systems for future adaptive routing. In these approaches, the routing task is modularized into information and protocol layers. The information abstraction layer provides the required information for multiple routing protocols freeing designers from the low-level concerns of information gathering and tolerance to information source failures. However, these solutions are designed for specific network scenarios allowing only limited types of adaptations via a set of customized interfaces.

Finally, profile-based routing was proposed by Hansen et al. [7]. They point out that information contained in standardized device profiles, including device type, power supply, interface, rate of transmission, etc., can be utilized in the routing process to increase service availability and performance. At this time, a detailed description of their approach is unavailable.

7. CONCLUSION AND FUTURE WORK

In this paper, we explored the concept of a high-level information abstraction layer for the development of adaptive routing in WMNs and discussed the requirements of such a middleware approach. We proposed the use of our autonomic context management system, ACoMS, which is a middleware for context-aware computing designed to provide context provisioning services and context source re/configuration to multiple high-level context-aware applications.

ACoMS acts as the information abstraction layer for provisioning context information to support context-awareness in routing for WMNs. It simplifies the use of a variety of information sources in routing protocols, and enables experimentation, prototyping and development of complex routing

[3] http://cricket.csail.mit.edu/

protocols and metrics. ACoMS provides self-configuration of context sources required by routing protocols and run-time replacement of failed/disconnected context sources, providing a degree of fault tolerance. Defective context sources can be replaced by sensors of a different type provided that their sensed data can be pre-processed to the required type of context information.

Our next task is to perform a quantitive evaluation of our approach using simulations and our hybrid wireless mesh network testbed. As we experiment with the integration of new kinds of context information, we foresee the opportunity to choose dynamically between different routing protocols in addition to selecting between metrics.

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9. REFERENCES

[1] I.F. Akyildiz and Xudong Wang. A survey on wireless mesh networks. *Communications Magazine, IEEE*, 43(9):S23–S30, Sept. 2005.

[2] O. Battenfeld, M. Smith, P. Reinhardt, T. Friese, and B. Freisleben. A modular architecture for hot swappable mobile ad hoc routing algorithms. In *Proceeding of Second International Conference on Embedded Software and Systems, 2005.*, page 8., 16-18 Dec. 2005.

[3] Douglas S. J. De Couto, Daniel Aguayo, John Bicket, and Robert Morris. A high-throughput path metric for multi-hop wireless routing. In *MobiCom '03: Proceedings of the 9th annual international conference on Mobile computing and networking*, pages 134–146, New York, NY, USA, 2003. ACM.

[4] Richard Draves, Jitendra Padhye, and Brian Zill. Comparison of routing metrics for static multi-hop wireless networks. In *SIGCOMM '04: Proceedings of the 2004 conference on Applications, technologies, architectures, and protocols for computer communications*, pages 133–144, New York, NY, USA, 2004. ACM Press.

[5] Richard Draves, Jitendra Padhye, and Brian Zill. Routing in multi-radio, multi-hop wireless mesh networks. In *MobiCom '04: Proceedings of the 10th annual international conference on Mobile computing and networking*, pages 114–128, New York, NY, USA, 2004. ACM.

[6] V. Dumitrescu and Jinhua Guo. Context assisted routing protocols for inter-vehicle wireless communication. In *Proc. of IEEE Intelligent Vehicles Symposium.*, pages 594–600, 6-8 June 2005.

[7] A. F. Hansen, T. Cicic, and P. E. Engelstad. Profiles and multi-topology routing in highly heterogeneous ad hoc networks. In *INFOCOM 2006, Poster and Demo session, Barcelona, Spain April 23-29.* IEEE, 2006.

[8] K. Henricksen and J. Indulska. A software engineering framework for context-aware pervasive computing. In *Proc. of the Second IEEE Annual Conference on Pervasive Computing and Communications (PerCom'04)*, pages 77–86, 2004.

[9] Karen Henricksen and Jadwiga Indulska. Developing context-aware pervasive computing applications: Models and approach. *Journal of Pervasive and Mobile Computing*, 2(1):37–64, Feburary 2006.

[10] Peizhao Hu, Jadwiga Indulska, and Ricky Robinson. An autonomic context management system for pervasive computing. In *Proc. of the Sixth IEEE Annual Conference on Pervasive Computing and Communication (PerCom'08) (to appear)*, March 17-21 2008.

[11] Peizhao Hu, Ricky Robinson, and Jadwiga Indulska. Sensor standards: Overview and experiences. In *Proc. of The 3rd International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP 2007)*, Melbourne, Australia, 3-6 December 2007.

[12] T. Johnson and D. Sadok. Context routing in heterogeneous pervasive computing fieldwork environments. In *Wireless Communications and Networking Conference, 2006. WCNC 2006. IEEE*, volume 1, pages 211–216, 3-6 April 2006.

[13] Jeffrey O. Kephart and David M. Chess. The vision of autonomic computing. *Computer*, pages 41–50, 2003.

[14] Eddie Kohler, Robert Morris, Benjie Chen, John Jannotti, and M. Frans Kaashoek. The click modular router. *ACM Trans. Computer Systems*, 18(3):263–297, 2000.

[15] Cecilia Mascolo and Mirco Musolesi. Scar: context-aware adaptive routing in delay tolerant mobile sensor networks. In *IWCMC '06: Proceeding of the international conference on Communications and mobile computing*, pages 533–538, New York, NY, USA, 2006. ACM Press.

[16] Marius Portmann. *Wireless Mesh Networks for Public Safety and Disaster Recovery Applications, Chapter in Wireless Mesh Networking: Architectures, Protocols and Standards.* Auerbach Publications (CRC Press), 2006.

[17] Claude Richard, Charles Perkins, and Cedric Westphal. Defining an optimal active route time-out for the aodv routing protocol. In *IEEE SECON 2005 (poster submission)*, 2005.

[18] Irfan Sheriff and Elizabeth Belding-Royer. Multipath selection in multi-radio mesh networks. In *Proc. of the 3rd International Conference on Broadband Communications, Networks and Systems, 2006. BROADNETS 2006.*, pages 1–11, 1-5 Oct. 2006.

[19] A.P. Subramanian, M.M. Buddhikot, and S. Miller. Interference aware routing in multi-radio wireless mesh networks. In *Proc. of the 2nd IEEE Workshop on Wireless Mesh Networks, 2006. WiMesh 2006.*, pages 55–63, 2006.

[20] Y. Yang, J. Wang, and R. Kravets. Designing routing metrics for mesh networks. In *Proceedings of the IEEE Workshop on Wireless Mesh Networks (WiMesh)*, 2005.