Towards Real-time Event-based Communication in Mobile Ad Hoc Wireless Networks

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ABSTRACT

Most previous work on real-time event-based communication has assumed infrastructure-based networks. The underlying assumption of this work is that application components are stationary and that a fixed network infrastructure exists to facilitate communication between them [1]. Ad hoc wireless networks comprise sets of mobile nodes connected by wireless links that form arbitrary wireless network topologies without the use of any centralized access point. Ad hoc wireless networks are inherently self-creating, self-organizing and self-administering [2]. Such highly mobile, dynamic networks do not satisfy the design assumptions for previous real-time event-based communication.

In this paper we propose a conceptual model for real-time event-based communication in mobile ad hoc wireless networks. Our model is designed to alleviate the impediments to real-time event-based communication that are characteristic of a mobile ad hoc wireless environment, for example, dynamic connectivity, unpredictable latency and limited resources.

The model we propose is the first to directly address the issue of achieving timeliness and reliability for real-time event-based communication in dynamic mobile ad hoc wireless networks. In this paper we describe the impediments imposed by ad hoc wireless networks on real-time event-based communication, and propose techniques, in particular prediction, to help overcome them.

1. INTRODUCTION

The inherent loose coupling that characterizes applications in a wireless ad hoc network promote event-based communication as a natural design abstraction for a growing class of software systems [1]. The event-based communication model is well suited to addressing the requirements of wireless mobile computing applications [3]. In this domain the infrastructure or the ad hoc network model may be used for wireless communication. Infrastructure wireless networks use access points or base stations to mediate communication between mobile application components. Ad hoc wireless networks comprise sets of mobile nodes connected by wireless links that form arbitrary wireless network topologies without the use of any centralized access point or infrastructure. Ad hoc wireless networks are inherently self-creating, self-organizing and self-administering [2].

The event-based communication model is supported by several middleware services that use the event paradigm as a high-level communication abstraction. The underlying assumption of most of these services is that application components are stationary and that a fixed network infrastructure exists to facilitate communication[1, 3-5]. The complexities introduced by the mobile ad hoc wireless network model, for example instantaneous topology changes, are not considered. For event-based communication to scale to mobile ad hoc wireless networks it is important that the designs of middleware services are not based on many of the assumptions made for fixed infrastructure networks, such as low latency, abundant bandwidth, static topology, and most importantly centralized control [1].

With the increased research in ad hoc networks in recent years new application domains such as communication between mobile robots and inter-vehicle communication have evolved. Timely communication is essential to allow applications in these domains to be realized. The real-time event-based communication paradigm has been recognized as an appropriate high-level communication scheme to connect autonomous components in large distributed control systems [6]. The challenge remains to extend real-time event-based communication to mobile nodes in a dynamic wireless ad hoc network where the assumption of a fixed infrastructure is not applicable.

In this paper we discuss the assumptions upon which existing (real-time) event-based communication models rely. We pay particular attention to the extent to which these assumptions are applicable in ad hoc wireless networks. We identify the characteristics of ad hoc wireless networks and how these characteristics inhibit real-time event-based communication. We propose a conceptual model for real-time event-based communication that relies on predictive techniques to alleviate the impediments to real-time event-based communication that are characteristic of a mobile ad hoc wireless environment.

In the next section we review the assumptions and subsequent design decisions upon which existing real-time event-based communication models rely. We pay particular attention to the extent to which these assumptions are reasonable in the ad hoc wireless domain. The following section describes the limitations on real-time event-based communication due to the characteristics of mobile ad hoc wireless networks and is followed by a description of our conceptual model for real-time event-based communication to overcome these ad hoc wireless limitations. We finish the paper with some conclusions and a discussion of future work.

2. ASSUMPTIONS IN FIXED INFRASTRUCTURE NETWORKS

For real-time event-based communication models to be used in mobile ad hoc wireless networks it is important for their designs not to be based on many of the assumptions made for infrastructure-based networks, both wired and wireless. In this section we review the common assumptions and subsequent design decisions underlying some real-time event-based communication models for infrastructure networks and discuss the applicability of these assumptions in the mobile ad hoc wireless domain. The assumptions of particular interest are:

2a. Accessibility

In infrastructure networks there is an implicit assumption of known connectivity, in the absence of the failure of network components [7]. In event-based communication this assumption underlies the development of intermediate components such as event channels, [4, 5] or event dispatchers, [1, 3] which are often run independently and remotely to event producers and consumers. In these models the accessibility of the intermediary components is both assumed and critical, for all entities participating in event-based communication.

A serious impediment of ad hoc wireless networks is the limited area that can be covered by mobile application components using a wireless transmitter. In an ad hoc wireless network entities may be distributed over a potentially large geographical area and thus are unlikely to be able to maintain a permanent communication link to an intermediary [8]. Nodes in an ad hoc network communicate directly in a peer-to-peer fashion, which implies that event-based communication relies on the mutual accessibility of producers and consumers to disseminate events. In wireless ad hoc networks, mutual accessibility cannot be assumed. In addition wireless ad hoc nodes participating in real-time event-based communication are potentially mobile and move along trajectories that are not necessarily planned in advance. The unpredictability of node movement coupled with the limited area covered by wireless transmitters necessitates the omission of intermediate components providing system-wide services in the design of an event-based communication model for mobile ad hoc wireless networks.

2b. Known upper bound on the number of participating nodes

Real-time event-based communication models for fixed infrastructure networks often assume a known maximum number of nodes connected to the physical medium [5]. In contrast, ad hoc wireless networks have the potential to serve as a ubiquitous wireless network capable of interconnecting many thousands of devices [7]. Ad hoc wireless networks are created 'on-the-fly' as a result of the mutual discovery of two or more mobile devices with wireless interfaces. This feature of wireless communication, coupled with the dynamic mobility of wireless nodes to move within range of another wireless node, means there is potentially no upper bound on the number of nodes participating in an ad hoc wireless network. The unbounded network size leads to scalability issues due to the increased computational load and difficulties of propagating network topology updates within given time bounds [9], increasing the unpredictability of wireless connections and timely and accurate route and resource reservation decisions all of which effect time-bounded event transmission and propagation.

2c. Known resource requirements

In addition to the previous assumption of a known upper bound on the number of participating nodes, it is assumed that there are known resource requirements for event-based communication among the participants. For example, the TAO Real-time Event Service [10] and the Real-time Event Channel Model for the CAN-Bus [5], use this assumption to perform real-time medium-access scheduling off-line using a reservation-based scheme to avoid collisions by statically planning the transmission schedule; and perform off-line admission testing to check the correctness of the reservations for timing conflicts and temporal overlap. In contrast, mobile ad hoc wireless networks require a dynamic resource reservation scheme to handle the effects of dynamic mobility where resource requirements are not known in advance.

Summary The dynamic mobility of nodes in ad hoc wireless networks renders the assumptions of event-based communication for infrastructure networks inappropriate. STEAM [8], is an event-based middleware service designed for the mobile computing domain, specifically IEEE 802.11 LANs using the ad hoc network model. STEAM addresses some of the fundamental issues arising for event-based communication among mobile ad hoc wireless nodes, for example accessibility. Open issues relating to the characteristics of wireless networks (e.g. mobility, limited resources etc.) and their impact on the timeliness and reliability of real-time applications are not addressed. We discuss these issues in the following section. Our work will extend STEAM to provide real-time capabilities.

3. IMPACT OF AD HOC NETWORKS

In this section we discuss the impact of wireless characteristics on real-time event-based communication. The main characteristics of interest are:

3a. Dynamic connectivity

The absence of a fixed infrastructure means that nodes in an ad hoc network communicate directly with one another in a peer-to-peer fashion. The mobile nodes themselves constitute the communication infrastructure – a node acts as both a packet[1] router and an end host. As nodes move in and out of range of other nodes, the connectivity and network topology changes dynamically [11].

Communication between mobile nodes requires the received signal strength (RSS) to be adequate to connect to another mobile node. The RSS is continually changing due to the movement of the communicating and intermediary nodes even if they remain within range of each other. The RSS is also significantly affected by the terrain configuration [12] and the transmission power of the wireless device [13]. Terrain configurations may include hilly or mountainous areas, wooded or forested rural areas, urban areas with multistory buildings or low-density suburban areas. In addition, transmission range decreases as wireless power (e.g. battery life), reduces, causing significant weakening of the RSS. The changes in RSS lead to highly unpredictable connections between mobile nodes.

Unlike fixed infrastructure networks where link failures are comparatively rare events, the rate of link failure due to node mobility and changing RSS is the primary obstacle to routing in ad hoc networks [14]. Since the rate of link failure is directly related to node mobility, greater mobility increases the fluctuations in link quality, the volume of topological updates,

[1] We use the term "packet" as a generic name for the piece of encapsulated information that circulates on the network. It may contain real-time event information.

Wireless characteristic	Caused by	Impact on real-time event-based communication	Benefit of prediction
Dynamic connectivity (frequent link failure and possible partition)	*Mobility* *Variable RSS* *Terrain* *Power*	*1. Increased volume of topological updates* *2. Increased use of wireless and computational resources* *3. Inaccurate network information*	*Mobility prediction, partition anticipation and predictive routing and resource reservation reduce reaction time to topological change by finding new routes in advance of the failure of existing routes. Coverage estimation is used to calculate the accuracy of network information.*
Unpredictable latency	*Collisions* *Multi-hop routing*	*1. Unpredictable medium access latency* *2. Unpredictable route discovery and end-to-end event delivery latency*	*Preemptive routing and proactive resource reservation, coupled with time-bounded medium-access control, e.g. TBMAC.*
Limited resources	*Limited Bandwidth* *Limited power*	*1. Unpredictable medium access* *2. Limited event packet size* *3. Increase in link failures due to node failure*	*Power-aware and preemptive routing coupled with in-band signaling and piggybacking to reduce control overhead impact on the network*

Table 1: Using prediction to reduce the impediments of ad hoc wireless networks

the time spent processing the updates (e.g. for route discovery protocols), and congestion due to increased update transmissions and retransmissions. Link failures may also result in network partitions.

How does this highly dynamic connectivity impact the ability to perform real-time event-based communication? The topology changes introduced by node mobility and wireless link failures must somehow be communicated to other nodes. Since communication and computation resources, for example bandwidth and battery power, are limited in wireless ad hoc networks [15], any overhead must be kept to a minimum and additional communication delays due to an increase in the volume of topological updates must be avoided. We propose using a predictive architecture combining mobility prediction with partition anticipation to achieve predictive routing and resource reservation. In [16] and [17], the variance in RSS is used to anticipate network partitions. If the future state of network topology can be predicted it is possible to perform route reconstruction proactively in a timely manner [18], and seamlessly switch to an alternative good route before a break, minimizing the impact on real-time event-based communication.

Topology updates throughout an ad hoc network cannot happen instantaneously. Nodes may have inconsistent views of the network that may never be accurate [2]. Current QoS routing algorithms [19-21], require accurate link state (e.g, available bandwidth, packet loss rate, estimated latency etc.) and topological information. The time-varying capacity of wireless links, limited resources and node mobility make maintaining accurate routing information very difficult, if not impossible, in ad hoc wireless networks [22]. Routing for real-time event-based communication must ensure resource availability (e.g. bandwidth) whilst maintaining minimum latency [17]. Routing decisions may be compromised by inaccurate network information and time-bounded route determination, where optimal routes may not be found within the time available [15].

Decisions based on inaccurate information have unpredictable consequences that may be critical for real-time event-based communication. Coverage estimation techniques [16], calculate the probability that there are disconnected nodes due to lack of network coverage. Using coverage estimation we can predict the accuracy of a decision in the presence of disconnected nodes. This can help to reduce the number of incorrect decisions and communication unpredictability that is critical for real-time event-based communication.

3b. Unpredictable latency

Minimizing end-to-end latency is critical to achieve the timeliness requirements of real-time event-based communication. We pay particular attention to medium access and routing latency, as both are specifically affected by the characteristics of ad hoc wireless networks. Wireless transmissions in ad hoc networks are broadcast through a shared physical communication channel. Collisions in wireless communications can be caused by simultaneous transmissions by two or more wireless nodes sharing the same frequency band, or by the well-known hidden terminal problem [23]. The probability of collisions increases as the density of the wireless network increases. Collisions cause unpredictable latency for medium access that is unacceptable in real-time event-based communication where each mobile node must have time-bounded access to the wireless medium to transmit a real-time event. Time-bounded access is not achievable with a high probability in the presence of unpredictable collisions and retransmissions.

The lack of a fixed infrastructure and the limited power of wireless mobile nodes that limits the transmission range, means that wireless nodes are designed to serve as routers if needed. The result is a distributed multi-hop network with a time-varying topology where routes are typically short-lived [24]. The latency involved in route determination might be quite significant and may be increased by the use of incomplete network information. The unpredictable latency for route determination and medium access (encountered at each hop) makes the estimation of end-to-end delivery latency, which is critical in real-time event-based communication where timeliness guarantees are required, very difficult and with a high probability of being inaccurate. Proactive and preemptive routing [17] attempt to seamlessly switch to a good route before a link failure occurs minimizing both the transmission latency and the jitter, which is essential for real-time event-based communication. Reducing the latency experienced at each hop by reducing the hop distance of a route is also important.

The TBMAC protocol [25], reduces the probability of collisions by providing each wireless node with time-bounded access to the medium with a high probability. In addition, TBMAC uses an admission test to limit the impact of changes in network density on the volume of collisions. We will use TBMAC to provide predictable medium access latency for real-time event-based communication and investigate the open issue of predictable multi-hop routing using TBMAC.

3c. Limited resource availability

In mobile ad hoc wireless networks the available bandwidth is very limited and some wireless devices have severe energy constraints, relying for example on battery power [26]. Hence, communication is an expensive operation in mobile ad hoc wireless networks in terms of bandwidth and energy consumption and therefore any additional control packet overhead (e.g. resource reservation, routing and scheduling) must be kept to a minimum. Additional control packets increase the competition for network resources (e.g. bandwidth, medium access etc.) for all (control and data) transmissions. Using in-band signaling [15], and piggybacking techniques, the volume and processing of additional control overhead can be significantly reduced. The cost associated with these techniques is an increase in the size of the communicated packet, with an implicit increase in the bandwidth required for each packet. In real-time event-based communication the size and volume of real-time events generated may be limited by bandwidth constraints.

The relationship between transmission power and battery life has been investigated in [13], where Campbell et al. identify that a critical design issue for wireless ad hoc networks is the development of suitable communication architectures, protocols and services that efficiently reduce power consumption thereby increasing the operational lifetime of the wireless device. In order to provide sufficient battery life, transmission power must be conserved, limiting the transmission range, data rate and the communication activity (sending and receiving) and processing speed of the device [24]. Increasing battery life will help reduce the number of link breaks caused by node failure, and thus the volume of topological updates, the competition for scarce resources, and communication unpredictability that impede real-time event-based communication.

Summary To achieve real-time event-based communication in a mobile ad hoc wireless environment the impact of the ad hoc wireless network characteristics previously identified must be limited. We propose that prediction is essential to limit these wireless ad hoc characteristics. Table 1 introduces how predictive techniques limit the impediments of the wireless ad hoc environment for real-time event-based communication.

4. PROPOSED CONCEPTUAL MODEL

To achieve real-time event-based communication in a dynamic mobile ad hoc wireless network, the unpredictability inherent in the environment must be reduced. In this section we outline a conceptual model based on prediction for timely event-based communication between mobile nodes. Figure 1 identifies the components and high-level interactions among them.

Bounding the area of interest in an ad hoc network makes a large network appear smaller, but more importantly for real-time communication, it makes a highly dynamic topology appear less dynamic. Our approach is to partition the network into dynamically organized zones, similar to proximity groups [16], which bound the number of participants, the area for maintaining topology information and the area within which event information is propagated. The components of the conceptual model cooperate to maintain the timeliness and reliability requirements within a proximity-bounded zone.

The focus of our design is to reduce reaction to dynamic mobility and topological change by prediction. The admission control and adaptation components interact with the predictive architecture to make proactive decisions in advance of network change [27] .

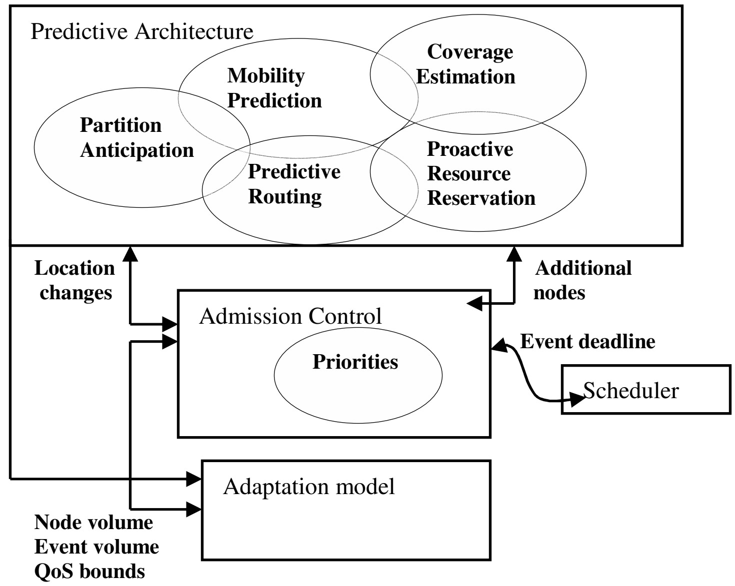

Figure 1: High-level conceptual model

- *Predictive Architecture:* predictive techniques are used to reduce the impact of dynamic topological changes within a zone. Location-awareness is key to determining the mobile nodes within a zone at a point in time. In our opinion location-aware routing [28] is central to achieving proximity-bounded communication in a mobile network. We plan to extend this work to predict the future location of mobile nodes. Using this information future node movement into a zone, the impact on routing, resource reservation, and guarantees for timeliness and reliability for the zone can be predicted in advance.

  The ability to predict node movement contributes to achieving probabilistic guarantees of path availability due to link failure caused by node mobility. Other reasons why a link may fail, such as environment conditions or battery usage, must also be considered to avoid or anticipate network partitions. Using partition anticipation based on [16] coupled with proactive and preemptive routing [14, 17, 24] and resource reservation, we aim to improve the re-routing process by attempting to find new paths prior to the failure of existing ones. To obtain mobility independent real-time guarantees, a mobile host would need to make advance resource reservations at predicted locations they may visit during the lifetime of the communication [27]. Accurate mobility and location prediction is critical for limiting the overhead of excessive resource reservation.

- *Admission Control:* bounding the area of interest for real-time event-based communication implicitly limits the number of participating nodes to those within the bounded area. We apply explicit admission control policies within the zone to further reduce the number of participating nodes and the hop distance for routes within the zone [24]. The admission control policies reflect the impact of the number of participating nodes in the zone on the timeliness and reliability guarantees for a real-time event given the resources available when the real-time event is raised.

Using predictive techniques to detect future node movement is essential for deciding the admission policy to use. For example, if resource usage is nearing maximum capacity what temporal and reliability guarantees can be made for future nodes moving into the zone and what impact does the class of real-time event have on admission control decisions?

- *Adaptation Model:* an important aspect of achieving timeliness constraints is dependable QoS adaptation [29]. However in contrast to [29] mobility is a critical consideration. The predictive architecture detects topological changes and initiates proactive routing and resource reservation. QoS adaptation may be necessary to reflect the new routes and resources available. The speed of node movement and the class of event for delivery impact the urgency of time-bounded delivery of a real-time event and impacts any QoS adaptation. Information from the predictive architecture is essential for limiting the reactive QoS adaptation required.

We propose a conceptual model to make the dynamic topology of mobile ad hoc networks less dynamic and therefore more suitable to real-time event communication. We propose that prediction is essential to reduce the reaction to dynamic node mobility and therefore essential for real-time event-based communication in wireless ad hoc networks.

5. FUTURE WORK

A critical requirement for our future work is to determine the cost of prediction, in terms of increased overhead and the consequences of wrong predictions on real-time event-based communication. For example, a high number of new route requests may be initiated because a link becomes suspect but never breaks, resulting in increased latency and overhead arising from the discovery of a new route with potentially decreased resources and reliability.

Our future work must also determine the impact of the wireless application on the ability to predict. For example, a wireless car with a known speed and trajectory will be limited by the restrictions of the vehicle and the road. These are application specific parameters that increase the probability of a correct prediction that may not be available in other wireless applications, for example a multi-player game which is characterized by a dynamic number of players of varying speeds and trajectories in a potentially random game-playing area that may not be suitable to wireless communication. For example, a densely populated urban area has many possible impediments to wireless communication that may significantly reduce the signal strength and the probability of correct predictions.

6. CONCLUSION

We have outlined our approach to the complex problem of achieving real-time event communication in infrastructure-free wireless networks. We outlined the limitations of previous event-based and real-time event communication models when applied to the ad hoc wireless domain. We proposed an outline of our event-based communication model, which focuses on limiting the unpredictability of wireless communication by prediction. We described a predictive architecture for predicting node mobility, link failure and for anticipating partitions. Using this predictive architecture and QoS adaptation strategies relating to the criticality of the real-time event, we have proposed a novel approach to achieving real-time event-based communication in ad hoc wireless networks.

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