Reliable Dissemination of Mission-Critical Content over Heterogeneous Wireless Networks

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I. INTRODUCTION

In recent years, situational awareness in emergency response and military domains have attracted unprecedented attention. One important operation for realizing such situational awareness is content dissemination, i.e., the distribution of situation-related information to some or all participants (an example scenario is illustrated in Fig. 1). Its key characteristics are the following – (i) participants scattered around the mission site may have limited infrastructure access and the connectivity between one another might be intermittent; (ii) any participant carrying a mobile device can be a producer of information and start a dissemination; (iii) the information can be rich in content (e.g., in the form of images, voice, video, etc.) and have strong temporal and/or spatial relevance (i.e., may be of no use outside a certain geographical region and/or after a specific time point). (iv) Reliability and timeliness of a dissemination is critical. As an example, a fire fighter at a rescue site may create a video alert and send it to other rescue personnel to warn them about a gas leakage he has detected. Advances in wireless-connected devices and ad-hoc networking technologies have made such scenarios possible.

In such dissemination applications, as the disseminated data is mission-critical, the overriding goal is *reliability* – to reach as many intended recipients as possible, or in some cases to reach at least specific number of intended recipients. Meanwhile, *timeliness* (short latency being incurred before recipients receive the content), *transmission efficiency* (small number of messages/bytes being transmitted, and accordingly low energy is consumed), and *storage efficiency* (small amount of storage is used) are important as well.

However, to enable reliable content dissemination over wireless networks, we face several challenges. First, due to the uncertainty of wireless transmissions, data can easily get lost or corrupted in the air. Transport protocols such as TCP (Transport Control Protocol) do not deal with one-to-many communications, while existing multicast/broadcast protocols designed for wired networks do not fit well in wireless networks. Second, Because of the dynamic topology changes caused by mobility, accurate topological knowledge (both local knowledge and global knowledge) is always hard to obtain. The disseminator may or may not know how many potential receivers there are as well as who they are. Moreover, as devices can move arbitrarily, they sometimes form a connected network, and sometimes have intermittent connectivity between one another. Third, the data in consideration is generated at the application layer; it differs from data generated at lower layers primarily in that it is potentially of much larger size. Given that the size of the data unit that can be handled directly on the medium is limited, reliable delivery of large content to all receivers is difficult [1]. Finally, wireless networks in reality are heterogeneous in terms of the capability of the participating devices and the wireless technology through which they communicate.

Fig. 1. An Example Scenario

Information dissemination in general has been studied in both wired and wireless networks. Although content distribution in wired networks (e.g., BitTorrent, CREW [2]) has attracted a huge amount of research efforts, its counterpart in wireless networks has not gained sufficient attention. Rather than large contents that are generated at the application layer, much prior work has studied the dissemination of small-size data (e.g., generated at lower layers of the network stack) [3] [4] [5]. In those cases, the foremost objective is not reliability but rather transmission efficiency. Ad-hoc network multicast protocols (e.g., [6] [7]) would be overkill if used for broadcast – all nodes participate in overlay construction and maintenance, which is expensive especially if nodes can move arbitrarily. Moreover, they aim at providing best-effort services, and do not offer reliability guarantees. Many existing approaches to dissemination attempt to modify the MAC (Medium Access Control) layer so as to enhance the reliability of every single wireless transmission (e.g., using a TDMA-based scheme instead of a CSMA/CA-based scheme). This is an expensive approach because it requires that the firmware on existing mobile devices be re-engineered to meet the needs of particular applications. We hence take a middleware approach in our study, which leaves the lower layer mechanisms untouched. A middleware solution will simply lead to a software package that provides programming interfaces to applications, and thus can be deployed directly on off-the-shelf mobile devices.

II. Our Research Work

Our research in this area basically falls into two categories: (ii) instant dissemination in connected networks and (ii) spatial dissemination in disconnected networks.

A. Instant Dissemination in Connected Networks

One specific problem we have looked at is content dissemination over a connected network – a group of mobile users autonomously form an ad-hoc network using Wi-Fi connectivity, where one or several users generate files with large content and disseminate the files in real time to all other users in the network. An example is the following application being developed by the Orange County Fire Authority. During disaster relief, fire trucks, ambulances, police cars and helicopters gather at the rescue site. Any of them can generate maps annotated with hazard information (e.g., chemical leakage) or take snapshots of nearby regions, and share them with all others in real time. The rescue personnel thus keep their situational awareness in sync. These contents are securely transmitted via an ad hoc mode 802.11 variant protocol at the 4.9GHz public safety frequency band. In scenarios, in addition to speed, applications may require guarantees on the reliable delivery of mission-critical data. The reliability needs of applications might vary – some demand to cover at least a certain percentage of nodes; others desire to reach all possible recipients.

A large portion of prior work on broadcast in ad-hoc networks has focused on dissemination of routing-related data [4]. Rather than reaching all potential recipients, the goal there is to send small-size control data to specific destination(s) whose location(s) are unknown. Although there has been work on the dissemination of large objects in wireless sensor networks [8], the assumption there is that the sensors are pre-aware of the disseminations. To address the varying needs of dissemination applications, we, without making heavy assumptions, develop a distinct middleware approach, which aims at providing reliability guarantees while seeking the balance between reliability and other aspects of performance [9]. Our approach decomposes the dissemination task into two concurrent subtasks – (a) awareness assurance, which assures recipients receive the metadata, and (b) data diffusion, which provides guaranteed delivery of the actual content data to dissemination-aware recipients. As data diffusion is relatively straightforward using concurrent push and pull, we thus reduce the dissemination problem to a fast network traversal problem (which is NP-hard). We propose to use special walker messages for network traversals, and develop a heuristic which finds near-optimal solutions to the traversal problem. The heuristic optimizes both the cover time and the termination time of traversals. It is the key to guaranteeing dissemination reliability while still achieving timeless and efficiency. Through a smart instantiation of the components and their parameters, our approach is able to support adaptive reliability as requested by individual applications, and achieve a tradeoff between reliability, timeliness and efficiency.

B. Spatial Dissemination in Disconnected Networks

Another problem we have been working on is what we call spatial dissemination, in a challenged networking environment where mobile users are not connected as a cloud at any time. In spatial dissemination, rather than sending messages to specific receivers, mobile users are able to leave messages at a physical location, so that other users who are at the location thereafter will receive the message although they never have connectivity to the sender. This could be useful in many scenarios where the generated information has strong location relevance and the information producer at the publication time does not know who will need this information. For instance, at a rescue site, a fire fighter publishes a "area cleared" voice message (with detailed descriptions about the area) to the location he has just inspected, so that other rescue personnel who later enter the area will be notified of the status and thus do not need to repeat the work. In such scenarios, since devices propagate information in a store-carry-and-forward fashion, other than reliability, storage and transmission efficiency also needs to be optimized.

Very limited existing work has adequately addressed the needs of spatial dissemination applications [10]. Essentially a flooding-based scheme, Epidemic routing [11] overwhelms all participating devices some of which might be far from the relevant location of the message. Whereas, a scheme that simply designates the devices at the location of the message as the carriers of it [12] would not work well if it happens at a time point that no device is present at the location. We learn the lessons observed from these techniques, and hence develop a protocol which aims to achieve the balance between reliability, storage and transmission efficiency. Without making assumptions on mobility patterns, our approach attempts to control how the messages move so as to make them stay at the specified location. It determines how many copies should be generated for each message by finding a near-optimal solution to the geometric covering problem. It also takes into consideration practical issues in real deployments of spatial dissemination services. It adopts efficient purging strategies to deal with cache overflows, and provides mechanisms to tolerate the heterogeneities of device capabilities.

III. Implementation and Evaluation

In order to determine the feasibility of our approaches, we have implemented them on real mobile devices. The devices we use include Nokia N800 Internet Tablets [13] (the operating system is a modified version of Debian GNU/Linux [14]) and Nokia N95 8GB smart phones [15] (Symbian S60 platform 3rd version [16]). Our proposed protocols are encapsulated in a middleware suite which offers a variety of wireless peer-to-peer communication services to applications. Depending on the dissemination needs of the application, individual protocol modules are invoked with appropriate parameters. For instance, for an instant dissemination, the paths of the files to be disseminated as well as the desired reliability level are provided; whereas for a spatial dissemination, in addition to the message content, its location relevance and time relevance are specified.

Although we test our approaches in real world settings, the experiments are constrained by the small number of devices we have and the limited topologies we can generate. In order to evaluate the performance of our protocols under a variety of network scales, conditions and mobilities, we further examine them using simulations. Our simulation experiments are conducted using the QualNet v4.0 [17] simulator. We compare our protocols with existing techniques and other design options to show their advantages. Moreover, we investigate the impact of various environmental factors, device heterogeneities and content heterogeneities to determine their resilience.

IV. Concluding Remarks

In addition to the problems we have actively looked at, there are many other open research questions concerning reliable disseminations for realizing situational awareness. For example, how to reliably disseminate a large file over disconnected wireless networks is a big challenge. Moreover, how to exploit multiple connectivity (rather than Wi-Fi ad-hoc connectivity alone) to facilitate the operations is of great interest too. We believe that further work at the middleware layer will be able to resolve these issues.

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