Computer Communications 55 (2015) 4–21

Contents lists available at ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

A wireless multi-hop protocol for real-time applications

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ARTICLE INFO

Article history:
Received 12 February 2013
Received in revised form 20 August 2014
Accepted 22 August 2014
Available online 30 August 2014

Keywords:
MANET
Real-time networks
Priority-based scheduling
RT-WMP

ABSTRACT

Mobile Ad-hoc NETworks (MANETs) have been gaining increasing popularity in recent years thanks to their ease of deployment and the low cost of their components. The routing protocols in ad hoc networks face the challenge of establishing and maintaining multi-hop routes while complying with mobility, bandwidth limitation and power constraints. The already demanding problem of offering wireless communication in a MANET becomes more complicated in the case of real-time systems where the loss or late arrival of a single item of data can cause serious problems. In this article, we propose a real-time wireless protocol for MANET capable of timely delivery of data. Taking advantage of a cross-layer design, it includes a novel medium access control mechanism and routing algorithm based on the link-quality among the nodes belonging to the network. The protocol manages message priority and is capable of multi-hop communications. It has been conceived mainly to provide real-time wireless communication for small robot teams, making possible the sharing of information such as kinematics or laser data. The validity of the protocol is proven by an in-depth theoretical analysis of its real-time characteristics and performance and through a set of real-world experiments.

1. Introduction

Mobile ad hoc networks (MANETs) represent complex distributed systems comprising wireless mobile nodes that can freely and dynamically self-organize into arbitrary and temporary, ad hoc network topologies. This allows people and devices to seamlessly internetwork in areas with no pre-existing communication infrastructure, e.g., disaster recovery environments [1]. MANETs have been gaining popularity in recent years thanks to their ease of deployment and the low cost of their components. No wired base station or infrastructure is needed since each host communicates one with another via radio packets. In multi-hop networks, routing protocols are additionally challenged with establishing and maintaining multi-hop routes in the face of mobility, bandwidth limitation and power constraints.

Distributed real-time systems have an important presence in our technological society, for example in industrial control, automotive or aerospace applications. Correctness in a real-time system depends not only on the logical results of computation (logical correctness) but also on the times in which results are produced (timing correctness) [2].

In distributed real-time systems, logical and timing correctness depend also on the delay that the communication network introduces. This means that the communication network must be considered as a part of the real-time system and must be able to deal with timing issues. In other words, message deadlines (defined as the instant of time by which the execution of a job is required to be completed [3]) *must be met* as well as proper causal ordering ensured in distributed real-time systems. This requires that real-time protocols must offer timing and bounded end-to-end delivery delay guarantees. This requirement in turn leads to the need for controlled and deterministic access to the medium [4]. Several real-time communication protocols have been developed in recent decades, especially for industrial and professional use. Some examples are the CAN bus [5] (used principally in vehicles), PROFIBUS [6] for field bus communication in automation technology or the Factory Instrumentation Protocol (FIP) [7]. However, there are various distributed real-time applications [8,9] that must be based on wireless communication networks, such as multi-vehicular or multi-robot control and coordination, sensor networks, and non permanent installations. With the progressive introduction of wireless networks, many research projects have tried to transfer solutions for wired networks to the wireless medium. However, on the one hand, wireless networks are, in general, less reliable than wired ones, the probability of errors being much higher. Moreover, the fact that nodes are not able to listen to the channel

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http://dx.doi.org/10.1016/j.comcom.2014.08.012
0140-3664/

while transmitting aggravates the problem of collision detection and resolution. The vast majority of wireless protocols (like for Example 802.11 or 802.15.4) rely on random backoff mechanisms which introduce a high degree of unpredictability into the Medium Access Control (MAC) layer.

In light of all these issues, the scientific community is divided on the possibility of supporting hard real-time traffic via wireless communication. This is understandable considering that a single missed deadline can provoke a total system failure. However no system is exempt from errors or problems. Even a very robust system can suffer from electrical or mechanical problems that can jeopardize its correct behaviour. Real-time protocols rely on the fact that the probability of errors is below a certain reasonable threshold. Ethernet and real-time Ethernet, for example, manage Bit Error Ratios (BERs) of about 10^{-10}. This means that a 100 Mbps saturated network suffers from an error every 100 s or for each 1.215 GB transferred. Thus, a common hard real-time system must be able to manage at least this probability of error without collapsing into total failure. Obviously it is impossible to obtain such BERs in wireless communications (they are at least a couple of orders of magnitude apart), at least with the current technology. However, if an actual system can tolerate higher probability of error than those mentioned above, then wireless communication is a real possibility. In these cases it is possible to speak at least of *firm* real-time communication over wireless. In cooperative robotics applications this is sometimes enough since infrequent deadline misses may be tolerable even if they degrade the quality of service of the system. In such applications, robots need to collaborate to achieve a common goal. Generally, sensors on robots produce periodic updates that must be transmitted to other members of the team respecting time constraints in order to achieve such collaboration [10]. The strictness of timing requirements depends on the specific application or system, but in some of these the loss of a single or multiple deadline is not necessarily a great problem given robot autonomy.

In this paper, we provide a detailed presentation of the Real-Time Wireless Multi-hop Protocol (RT-WMP). The protocol, introduced in [11], is analyzed in-depth from the point of view of performance and effectiveness. Both theoretical and practical analyses have been carried out by means of an extensive new set of simulation and real-world experiments. Also, several new features and characteristics are presented. The RT-WMP is then compared with the OLSR protocol [12] to show the differences in terms of offered bandwidth and mobility management. Moreover an unpublished detailed analysis of its real-time characteristics and timing (needed for real-time planning) is presented in Section 4.

This paper is organized as follows. In the following section we present a brief review of related works addressing real-time wireless protocols and the inadequacy of general purpose protocols for real-time applications. Section 3 provides a review of the basic features of the RT-WMP protocol. An analysis to validate the RT-WMP real-time features is exposed in Section 4. Section 5 describes to a theoretical evaluation of the RT-WMP while Section 6 presents a real evaluation, highlighting performances in terms of end-to-end delay and bandwidth, fairness, and a comparison between RT-WMP and a general purpose protocol. Section 7 summarizes the main conclusions and future work.

2. Related work

Supporting real-time communications in wireless environments is not an easy task due to the higher error probability that this medium suffer from, with respect to its wired counterpart and the need for deterministic timing that general purpose protocols cannot guarantee. In this section an explanation about the inadequacy of common used wireless protocols for real-time and especially for mobile robotics communication is provided and a review of state of the art is discussed.

2.1. General purpose protocols and mobile robotics

Commercial mobile robots usually have some type of communication interface such as, for example, 802.15.4/Zigbee, Bluetooth or IEEE 802.11. However, the latter has become the *de facto* standard for outdoor robotics thanks to its wide diffusion and good coverage range. However, like the other protocols mentioned above, the IEEE 802.11 does not have a deterministic behaviour since it uses a random backoff mechanism for medium access and collision resolution. This makes its use impossible in real-time networks where all phases of the communication are required to be time-bounded. Moreover, the protocol is not able to manage (natively) multi-hop peer-to-peer communication and mobility is restricted to the collision domain shared by the members of the network.

2.1.1. Random backoff

Neither the backoff nor the RTS/CTS mechanisms eliminate the possibility of collision. In fact, two or more stations can choose the same backoff period and begin transmission at precisely the same moment. Moreover, the presence of *random* factors in transmission deferral implies timing indeterminism in information exchange. This factor can lead to situations such as the false blocking problem [13] that can completely jeopardize the operation of a wireless network.

2.1.2. Multi-hop

The 802.11 was intended primarily to grant wireless access to the Internet by means of access points connected to the network infrastructure. In this configuration, all the stations must be able to communicate directly with the access point that distributes the frame acting as a relay. The ad hoc mode allows peer-to-peer communication but, as stated earlier, does not support multi-hop. Upper layer routing protocols such as AODV [14] DSR [15] or [16] are needed to implement this characteristic. However, regardless of the overhead introduced by the routing protocol used, end-to-end bandwidth is highly dependent on network topology and the number of nodes that share the same collision domain. In fact, according to [17], a transmission can cause interference in a range larger than the communication range (almost twice the latter). Nodes within the *carrier sensing range* of a transmitting node can sense the carrier of the sender even if they cannot hear the frame, and thus delay its transmission. According to our research, in relatively small wireless networks there can be situations where each node can only communicate with its predecessor and its successor, and carrier sensing does not allow spatial reuse (i.e. only *one* node can transmit at a time).

In short, sometimes neither spatial reuse nor broadcast dissemination is possible in small networks. Even though use of the 802.11 protocol is very widespread thanks to its notable characteristics such as its relatively high bandwidth, good communication range and the low cost of the devices, it does not constitute an option for real-time communication in robotics due to the lack of multi-hop support and the indeterminism that affects the MAC layer.

2.2. Wireless real-time protocols

The literature on how to support real-time communication in wireless environments is not very extensive. However, several proposals have been put forward in the last few years following different approaches and paradigms. Some of the most representative are described below.