Composable Routing in Mobile Mesh Networks

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ABSTRACT

Small teams of cooperating robots have been shown to be useful in a myriad of applications, with robots communicating with one another in real-time, be it multimedia, motion control or position information. Their mobility leads to a dynamic network mesh topology through which communications have to be routed, interfering in intricate patterns that vary with time, with the number of active robots in the team, and with their relative positions. In this short paper we advocate that routing for small teams of cooperating robots benefits from global synchronization and immediate forwarding, supporting composability of communications in the time domain by isolating the paths of each flow in separate time slots.

1. INTRODUCTION

Cooperative robotics has been studied for several years [1][2] sinceteams of robots are useful in many applications, from search and rescue in catastrophic situations to manoeuvres in contaminated areas. In most cases the robots communicate with one another in real-time, forming a mobile mesh network that conveys time sensitive information such as live multimedia streams or motion and position controls [7].

Despite some cases in which the network could be deployed around a central access point [6], the typical approach is to use decentralised ad-hoc networks for their increased area coverage and topology flexibility. This, however, comes at the cost of routing requirements and associated propagation delays.

Ordinary asynchronous routing approaches [5] cause high levels of mutual interference across messages due to both arbitration-induced delays at medium access [9] and forwarding of traffic generated by other nodes. The medium access issue has been mitigated with token-passing [7, 8] and global synchronization using Time Division Multiple Access (TDMA) [4]. However, common implementations still suffer from mutual interference among message streams, the former due to global priorities and the latter due to forwarding. Thus, computing end-to-end delays requires knowing all message streams in the network and their paths, which prevents composability and is particularly complicated with dynamic network topology.

Recently, TDMA with immediate forwarding emerged as a solution to this problem [3]. This technique grants one exclusive slot to each robot in the team but confines the traffic generated by each node along its path to its own slot so that end-to-end delays can be computed without knowledge of the traffic generated by other nodes. Thus, achieving composability in the time domain, which is valuable when nodes can join and leave the network at run-time.

The protocol in [10] also follows a similar immediate forwarding principle but uses synchronous forwarding instead, over IEEE 802.15.4. In this case, forwarding nodes repeat the packet to be forwarded at the same time, with high precision synchronization, so that symbols interference constructively. Therefore, a packet can be flooded throughout the network in the time corresponding to its transmission in one link. However, it is unclear whether this method can be applied to WiFi in practice, given the modulation and bit rates used and therefore we consider traditional information propagation with store and forward.

This short paper presents an early comparison between two such forwarding techniques within a TDMA framework, namely immediate forwarding as in [3] and the traditional forwarding inside each node's slots, only.

2. TDMA FOR MOBILE ROBOTS

TDMA is a common temporal multiplexing technique that provides each node with an exclusive fixed duration transmission slot. These slots follow each other in a round that repeats continuously, consequently precluding medium access collisions. As long as the nodes continue respecting their slots, this collision-free characteristic is kept even when the network topology changes, or when some nodes temporarily move out of the team range or pass behind occluding obstacles. This property is extremely advantageous for teams of mobile robots.

TDMA implementation is commonly based on clock synchronisation with each node computing the time offset of its slot with respect to the start of the round. Alternatively, clockless synchronisation is also possible [4] as in Reconfigurable and Adaptive TDMA (RA-TDMA) that targets teams of robots. RA-TDMA adjusts the round to external interference and reconfigures it automatically, creating or deleting slots when robots join or leave the team. Moreover, this protocol also provides network topology tracking, which is key to support swift routing decisions. In fact, in the discussion that follows, we assume that all nodes have knowledge of the current topology and can compute routes on-the-fly.

3. MULTI-HOP FORWARDING

In most practical application scenarios, the robots in a team will move and change the network topology at run-time, with implications on the number of hops in the paths of on-going message streams. Moreover, the message forwarding policy will also impact strongly on the end-to-end delay. In this section we will address the behaviour of the common policy in which each node forwards traffic in its own slot, together with the traffic it generates, which we call *one-hop-per-slot*. We will also discuss another forwarding policy, in which the nodes forward their traffic immediately to the destination within their own slots, which we call *multi-hop-per-*

slot, and which we claim to be significantly better suited for routing time sensitive information in teams of mobile nodes.

3.1 One-hop-per-slot Forwarding

According to this forwarding policy each node can only transmit messages within its own slot. Therefore, when a node receives a message it checks if it is the final destination of that message and if so processes it. Conversely, when the node is only an intermediate hop, it queues the message and forwards it later in its own slot.

Concerning the timing behaviour of the communications, there are two issues with this forwarding policy. The first one is that messages from different nodes contend for the bandwidth of the slot of the node where their paths cross. In other words, the end-to-end delay of each message stream depends on the message streams originating from other nodes in ways that depend on the current network topology. A worst-case timing analysis, thus, requires knowledge of all message streams exchanged in the team.

Moreover, the alignment of the nodes in each message path may coincide or not with the temporal order of the respective slots in the TDMA round. When they coincide, the propagation of a message along the path can be relatively quick, potentially in one round. Conversely, if the physical alignment does not match the slots order in the TDMA round, extra rounds are necessary to convey the message along its path. Consequently, the end-to-end delays will vary widely depending on the actual topology, not only with the number of hops but also the actual message routes.

3.2 Multi-hop-per-slot Forwarding

This forwarding policy is complementary to the previous one in several aspects. In this case the nodes forward messages immediately, within the slot of the originating node. In particular, when the node is only an intermediate node, it checks if it still has time to forward the message within the current slot and if so, forwards it immediately. If the message does not fit the slot, then it is queued and its forwarding is resumed one round later, in the beginning of the next slot of the originator node. On its end, the originator node can only send the next message if the previous one has reached its final destination and there is still time inside its own slot. In a more efficient version, the originator can reuse the channel by triggering a new message when the previous one has reached its 3^{rd} hop and there is still time inside its own slot.

From a timing point of view, note that each message stream flows in the network within the slot of its originator, only. Thus, mutual interference with the traffic generated by other nodes is eliminated leading to a composable system in the time domain in what concerns the addition and removal of nodes in the team. Moreover, the forwarding is immediate and does not depend on the order of the slots in the TDMA round. Consequently, the end-to-end delays do not depend on the specific message path but just on the number of hops, resulting in significantly less variations with the actual network topology and in lower delays in the general case.

4. EXPERIMENTS AND OPEN ISSUES

We assessed our claim quantitatively with simulation, using OMNeT++ considering an IEEE 802.11g network with long preamble. We used unfavourable topologies, with five nodes in line, which maximizes the number of hops for the given number of nodes. The TDMA round was configured to 50ms resulting in slots of 10ms. All nodes were generating one message stream to other nodes in multi-hop point-to-point paths, at rates near channel saturation. The results confirmed that the *one-hop-per-slot* forwarding policy led to higher end-to-end delays than *multi-hop-per-slot* immediate forwarding [3]. Specifically, when forwarding over at least 2 hops and against the slot order, we had a reduction of the maximum delay within 60ms-70ms (more than 1 round) and the mean delay was reduced to between 68% and 82%. When transmitting in the same direction as the slot order, the difference was smaller but still visible, since the delay exhibited by the *one-hop-per-slot* forwarding policy dropped due to the favourable forwarding direction while it remained approximately constant with *multi-hop-per-slot* forwarding, also confirming the lower dependence of the latter on the network topology.

Moreover, we validated with simulation a worst-case response time analysis of the message streams subject to *multi-hop-per-slot* forwarding that considered the traffic sent by each node separately [3], thus confirming the desired composability property. Currently we are analysing the dependence of this approach on the accuracy of the topology tracking mechanism in high mobility scenarios.

5. ACKNOWLEDGEMENTS

This article is a result of the project NanoSTIMA, NORTE-01-0145-FEDER-000016, supported by Norte Portugal Regional Operational Programme (NORTE 2020), through Portugal 2020 and the European Regional Development Fund.

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