Communication Network Challenges for Collaborative Vehicles

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***Abstract*— Networked systems of autonomous mobile agents have emerged in a variety of applications such as collaborative robotics, unmanned aerial/ground vehicles, mobile sensor networks and disaster relief operations. These agents utilize wireless communications for distributed computing, control and decision-making. Due to their limitations on energy supply, design and implementation of efficient distributed algorithms are crucial for these systems. This paper reviews different design aspects of networks of collaborative vehicles. We survey existing methods of addressing physical (PHY) and medium access control (MAC) layer, routing, and geometric connectivity issues for such networks and show limitations of these designs that address only single layer issues. We argue that a system engineering framework is needed for the design of such systems.**

I. Introduction

Collaborative control of teams of autonomous mobile vehicles has gained much interest over recent years. Most applications of such systems require the vehicles to move in a coordinated manner while maintaining group connectivity for efficient flow of information. The applications often fall into two broad categories: *mission planning* and *surveillance/reconnaissance*. For *mission planning*, a group of vehicles move in a partially known terrain to reach a known target while avoiding exposure to stationary/moving threats and collision with obstacles. These applications rely heavily on collaborative path planning [22] - [24]. For *surveillance and reconnaissance*, the objective is to cover a known area in order to detect and localize unknown threats. Coverage problems have been widely studied in the literature [26], [27]. More complex applications such as search and rescue [28] integrate elements from both mission planning and surveillance problems. In [25], the authors consider the problem of formation shape control which requires the ensemble to move from an initial formation to a final formation while satisfying some performance requirements. Another interesting application is cooperative graph based model predictive search [29], in which a team of autonomous agents searches for a mobile target.

Except for the most trivial applications in which coordination can be achieved via mere sensing, effective communication is required to provide vehicles with timely information to assist them in decision making. First, the design of the control architecture should be robust to communication failures. Meanwhile, the communication network should be designed so that the control performance remains feasible. It is similar to the joint communication and control design for wireless sensor networks (WSN) [30], with the additional complexity dimension resulting from mobility of the vehicles. Some of the results in control and communication co-design for WSNs can be adopted and build upon in the mobile context. An example of control communication co-design for WSNs can be found in [31], in which the authors decomposed the design problem into PHY, MAC, network and application layers and formulated a cross-layer design approach.

In the sequel we provide a survey of existing literature on communication network design for collaborative vehicles. In Section II we address efficient PHY and MAC layer protocols. Routing schemes for collaborative vehicles are considered in Section III. Section IV addresses the system level design issues and the cross-layer and joint design approaches are discussed in Section V.

II. Efficient PHY and MAC Protocols for Collaborative Vehicles

It is challenging to design and implement efficient PHY and MAC layer protocols for communicating collaborative vehicles, especially when they are micro-sized vehicles. With a small size, there is a strict limit on the type and number of devices that could be mounted on these vehicles. This directly leads to several issues in system design, e.g. energy efficiency, reliability and latency of the system.

A. *Transmission Power Control*

Transmission power control (TPC) is an important mechanism that is considered in both the PHY and MAC layers. In the PHY layer, adaptive modulation and coding schemes are deployed to increase the bandwidth in the presence of heavy workloads, or to decrease it to save energy. The MAC protocol can increase the transmission power when necessary to improve the probability of successful data transmission and thus the reliability of a link. TPC can also be used to reduce contention of the medium, where nodes only attempt to access the medium when necessary. As a result, TPC can be used to enhance network utilization and lower latency of the network.

Wang *et al.* first proposed a shutdown based approach to leverage the time-varying wireless channel [1]. Wireless transmissions are deferred to times when the channel can support energy-efficient communications, with various delay constraints considered. Schurgers *et al.* considered dynamic modulation scaling (DMS) as a more effective approach compared to shutdown based mechanisms [2]. DMS relies on the relationship between the energy and modulation level, and the ability of the radio to change its modulation on the fly. The authors considered DMS schemes based on QAM, PSK and PAM. Zurita Ares *et al.* proposed a Multiplicative-Increase Additive-Decrease (MIAD) power control scheme [3]. The MIAD power control is described by a Markov chain and is built upon a component-based software implementation. Quevedo *et al.* proposed a predictive power control scheme [4], where a centralized controller is developed to tradeoff between sensor energy expenditure and state estimation accuracy. The state estimation accuracy is measured by the expected value of the future covariance matrices provided by the associated time-varying Kalman filter.

Power Control Multiple Access (PCMA) [5] is a decentralized protocol that generalizes the on/off collision avoidance model to a more flexible variable bounded power collision suppression model. PCMA allows data transmission at minimum propagation ranges to maximize the spectral reuse and minimize energy consumption. Jung *et al.* [6] proposed a power control MAC protocol that varies the transmission power on a per-packet basis in order to mitigate asymmetric links caused by transmission power variations. Unlike other power control schemes based on different power levels for RTS-CTS and DATA-ACK, their protocol yields energy savings without degrading the network throughput. Lin *et al.* [7] proposed a closed-loop TPC protocol that approximates the transmission power using linear equations. The authors show that link quality can be approximated by the received signal strength using a linear equation. The major drawback of this method is its enormous memory consumption due to the huge amount of RSSI readings that must be cached. Correia *et al.* [8] proposed a protocol called Hybrid, which calculates the ideal transmission power using a closed control loop that iterates over the available transmission power in order to maintain a target link quality.

Performance analysis on power control can be found in [9], [10]. Gomez *et al.* [9] showed that per-link range adjustments outperform global range transmission adjustments by 50%. Ammari *et al.* [10] showed that by increasing the distance traveled at each hop, the end-to-end latency decreases at the cost of higher energy consumption .

B. *Duty-cycling MAC*

Duty-cycling is one of the main mechanisms for achieving low energy consumption in energy-constrained WSNs, where each node periodically cycles between an awake state and a sleep state. Key parameters of this approach include sleep time, wake time, and the energy consumed during the awake state and the sleep state. MAC protocols developed for duty-cycled WSNs can be categorized into synchronous and asynchronous protocols.

Synchronous protocols negotiate a schedule that specifies when nodes are awake and asleep within a frame. S-MAC [11] is a low power RTS-CTS based MAC protocol. The nodes in the network periodically wake up, receive and transmit data, and return to sleep. At the beginning of the awake period, nodes exchange synchronization and schedule information with their neighbors. After the synchronization information is exchanged, data may be transmitted using RTS-CTS-DATA-ACK until the end of the awake period. Adaptive listening is also introduced in S-MAC to tradeoff energy to latency. T-MAC [12] improves S-MAC's energy usage by introducing adaptive duty cycle. In T-MAC, nodes only listen to the channel for a short time after the synchronization phase, and if no data are received during a timeout window, nodes return to the sleep mode. T-MAC reduces energy usage for variable workloads; these gains however come at the cost of reduced throughput and increased latency.

Asynchronous protocols, on the other hand, rely on low power listening (LPL, also called preamble sampling) to link together a sender with data to a receiver who is duty cycling. Idle listening is reduced in asynchronous protocols by shifting the burden of synchronization to the sender. B-MAC [13] is a CSMA-based protocol that utilizes LPL and an extended preamble. In B-MAC, a sender precedes the data packet with a preamble that is slightly longer than the sleep period of the receiver. With the extended preamble, the receiver will wake up at some point during the preamble, detect the preamble, and remain awake in order to receive the data. B-MAC surpasses S-MAC and T-MAC in terms of throughput, latency, and energy consumption for most cases. However, it suffers from the overhearing problem and the long preamble dominates its energy usage. Z-MAC [14] is based on B-MAC but uses a TDMA schedule as a hint to enhance contention resolution. In Z-MAC, a node may try to transmit during any time slot via carrier-sensing; however the owner of that slot (assigned by TDMA) always has higher priority. By mixing CSMA and TDMA, Z-MAC is more robust to timing failures, time-varying channel conditions, slot assignment failures and topology changes than a TDMA protocol. X-MAC [15] introduces a series of short preamble packets each containing the target address information to avoid the overhearing problem and save energy on non-target receivers. X-MAC also uses strobed preamble to enable the target receiver to interrupt the long preamble via an early acknowledgement. X-MAC's shortened preamble significantly reduces energy usage at both the transmitter and receiver, reduces per-hop latency, and offers additional advantages such as flexible adaptation to both bursty and periodic data sources.

Fischione *et al.* analyzed the performance of the preamble sampling MAC protocols for a clustered network topology with unslotted IEEE 802.15.4 [16]. The authors provide accurate expressions in terms of delay, reliability, and energy consumption as a function of sleep time, listening time, traffic rate and MAC parameters. They also demonstrated the usage of these formulations in optimization of duty cycle of the nodes and MAC protocol parameters by minimizing energy consumption under latency and reliability constraints. The approach provides a significant reduction of the energy consumption compared to existing solutions.

III. Routing Schemes for Collaborative Vehicles

In general purpose wireless ad-hoc networks, routing protocols aim at discovering paths consisting of good quality links between pairs of source and destination nodes. However, standard multi-hop wireless routing protocols (e.g. AODV, DSR, and TORA) only discover paths between sources and destinations without considering quality of service (QoS) metrics.

On the other hand, accomplishing successful missions requires considering performance measures such as time and energy efficiency [35]. Some works in the literature implement policy-based approaches for multi-hop routing for collaborative vehicles. For example, references [32] and [33] emphasize the importance of policy based routing schemes for collaborative robots and propose a routing protocol called the source-initiated adaptive routing algorithm (SARA). Based on the symmetry of links in the networks, SARA can switch between policy-based routing and best-effort routing. The protocol is designed to require low computational resources on the nodes and is claimed to outperform standard wireless protocols. Reference [34] provides an implementation of an AODV-based protocol for a multi-robot system. The major shortcoming of the mentioned works is the lack of quantitative performance analysis.

In [35], we proposed a distributed policy based routing scheme for collaborative robots. Our approach is based on learning and updating routing tables based on local message passing. The scheme adaptively makes estimates of path costs from every source node in the network to a destination and uses these estimates to construct probabilistic routing tables in the nodes. It utilizes simulation-based approximate dynamic programming algorithms to learn the environment and update routing tables. A major shortcoming of the approach is its reliance on the distance based disk model for communications.

IV. System Level Design for Maintaining Communication Connectivity

A fundamental requirement for groups of collaborative vehicles is that the group should maintain its connectivity in the sense that nodes should be able to communicate with each other throughout the mission in order to increase survivability as well as satisfying other QoS measures. Spanos and Murray [44] translated wireless network connectivity constraints to distance based constraints. They formulated a notion of 'connectivity robustness' based on the range-dependent assumption of wireless connectivity and suggested that using this notion one can provably preserve connectivity using a receding-horizon approach. Maintaining line of sight (LOS) [36] is often too restrictive, especially when there are many obstacles in the terrain. Clustering based approaches [37], [39] have been proposed to alleviate this problem. These approaches employ flying aerial platforms (AP) as relay nodes that make the communication possible in the case of harsh environments. In [38] Perumal *et al.* addressed the problem of maintaining connectivity among ground clusters of moving agents by assigning a minimum number of APs to provide both connectivity and required traffic capacity. The problem was formulated as a dynamic clustering problem with AP inter-distance and capacity constraints. Reference [39] addressed distributed implementation of clustering algorithms and used a dynamic maximum-entropy approach.

Many works in the literature consider a graph theoretical approach to the problem of maintaining group connectivity. The unifying theme is to model the system as a state dependent dynamic graph and optimizing a notion of connectivity based on algebraic properties of the corresponding graphs [45]. Many attributes of an efficient graph such as its degree of connectivity and the number of spanning tress can be captured by the eigenvalues of its Laplacian matrix. If limitations on communication in the network can be modeled by constraints on the graph abstractions, optimization algorithms can be employed to determine desirable network formations [42] - [43]. An in-depth discussion has been provided by Mesbahi and Egerstedt [40, Chapter 7]. For a recent graph theoretic approach to connectivity control that employs methods from hybrid systems and sub-gradient optimization, the reader is referred to [41].

A major shortcoming of these graph based approaches is their reliance on the distance-based model for wireless communications. In reality the propagation of radio signals is affected by terrain specification, motion of other vehicles, transmitted power, interference, and other issues; these models are limited in their ability to capture the intricacies of complex terrains. To alleviate this problem, we considered different graph notions that are required to describe a network of mobile vehicles [46]. For collaborative control scenarios, an *action graph* determines which nodes need which nodes' information for a particular task; a *connectivity graph* describes which nodes can sense each other, and a *communication graph* describes the successful data transfer between them. Thereby, we can formulate the topology design problem as a problem of designing efficient communication strategies to satisfy certain requirements on the connectivity graph that respects the constraints imposed by the action graph. In [46], we considered an instance of this approach by providing a simulation-based framework to find efficient local connectivity patterns and used a clustering based method to provide system-wide connectivity.

V. Cross-Layer Approaches to Topology and Communication Design

The time, reliability and energy efficiency requirements often bring a complex interdependence among different layers of the underlying communication networks for collaborative control. In this situation, cross-layer design is an important paradigm to exploit this complex interaction among different layers of the protocol stack and reach maximum efficiency. Some recent works have addressed this issue. Although more difficult to analyze, these works provide more realistic settings that can consider multiple terrain-specific challenges such as fading, multi-path effects, interference and system latency.

A. *Cross-Layer Design of the Communication Networks*

Shah *et al.* first proposed an integrated protocol stack based on a randomized routing protocol and a randomized sleeping protocol [17]. The authors show that opportunistic routing and randomized sleeping can be jointly optimized to save energy while satisfying latency requirement. However, the impact of packet collisions is not considered in the protocol.

Breath [18] is a protocol based on a randomized routing, a randomized MAC and a randomized duty-cycling that are jointly optimized for energy consumption. In Breath, randomized routing reduces overhead due to node coordination, state maintenance and increases robustness on neighboring node failures. Randomized MAC can avoid contention on the wireless medium, and randomized duty-cycling allows the nodes to minimize their energy consumption. It is shown that Breath can minimize the energy consumption of the network while ensuring a desired packet delivery end-to-end reliability and delay. However, Breath is limited to scenarios with line topologies and source nodes at the edge of the network.

TREnD [19] is an energy efficient protocol that combines routing algorithm, MAC, data aggregation, duty-cycling and radio power control for clustered multi-hop WSNs. The parameters of TREnD are adapted by an optimization problem whose objective function is the energy consumption and the constraints are the reliability and latency of the packets. In TREnD, a hybrid TDMA/CSMA mechanism based on duty-cycling and a beacon mechanism is adopted at the MAC layer to offer high reliability and energy efficiency. The routing is subdivided into two parts: a static routing at the inter-cluster level, which is supported by a weighted TDMA scheme at the MAC layer, and a dynamic routing at the node level, which is implemented by forwarding the packets to a node within the next-hop cluster in a random path. TREnD shows good performance in terms of reliability, latency, low duty-cycling and load balancing for both static and time-varying scenarios.

B. *Opportunistic Communications*

In many collaborative control applications, there are a large number of micro vehicles, where the focus is to maintain an active communication network with enough nodes (i.e. vehicles) instead of a particular link between any two vehicles. On the other hand, due to multiple constraints, it is not wise to devote the transmission power needed to attempt reliable communications regularly for all links. In this scenario, opportunistic communications [20] can be utilized to improve the system performance, where the idea is to schedule transmissions in such a way that more packets will be sent over the links with better communication opportunities. In [21], we considered a joint communication and control problem for a group of agents with a given mission under the constraints of energy consumption and total operation time. We proposed an adaptive algorithm to attempt communications in an opportunistic way based on the qualities of the wireless channels as the agents move throughout the terrain. We showed that the protocol significantly improves system performance, both in terms of total operation time when the agents transmit only situational information and data throughput when additional data transmission is necessary.

C. *Joint Communication and Control Design*

Hsieh *et al.* [47] consider experimental construction of radio signal maps to maintain connectivity based on low level reactive controllers. Mostofi [48] combined objective functions from the PHY and application layer to develop communication-aware motion planning. Fink *et al.* [49] consider a joint network and application layer design to maintain end to end connectivity for teams of mobile robots.

VI. Conclusions

Various design aspects for maintaining connectivity and energy efficiency in communication networks for collaborative vehicles was surveyed. Limitations of graph theoretic approaches to control and communication co-design imply the need for cross-layer and joint design approaches. Due to the large number of design parameters and criteria, implementation of more elaborate cross-layer designs require a system engineering based approach for communication and control co-design.

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