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Scalable multi-radio communication in modular robots

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HIGHLIGHTS

- We present a multi-radio architecture for communication in modular robots.
- Our architecture guarantees constant bandwidth neighbor-to-neighbor communication.
- We prove our architecture scales to infinitely large networks 2D and 3D networks.
- The architecture is validated using a 45-radio testbed with real data loads.
- Results establish the feasibility of using radios for inter-module communication.

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ABSTRACT

Decentralized control of self-reconfiguring modular robots requires reliable inter-module communication. Communication links must tolerate module misalignment and implement the neighbor-to-neighbor communication model. In this paper, we propose a wireless system based on multiple radios per module that addresses these challenges. Although the capacity of general wireless mesh networks is known to rapidly decrease with network size, we show that a multi-radio single-channel system has constant capacity in square and cubic lattices of infinite size. We validate the performance of such a system in a testbed with 15 unactuated modules using synthetic data and a benchmark decentralized algorithm. We also demonstrate automatic neighbor detection. The main benefits of radio communication in modular robots are tolerance to module misalignment and to eliminate the tight coupling between communication and mechanical design necessitated by typical existing infrared and wired systems. Our results are the first to establish the feasibility of radio as the primary means of inter-module communication in modular robots.

1. Introduction

Self-reconfiguring (SR) modular robots rely on communication between modules to coordinate movement for reconfiguration and locomotion. Communication is also essential for sensing and perception in fusing data from many distributed sensors. We are interested in communication systems that are based on wireless radio frequency (RF) links. We envision wireless RF communication as a robust solution for implementing communication systems in SR robots.

Despite the central role communication plays in SR systems, robust and scalable inter-module communication remains a major research issue [1]. Communication between connected modules in existing SR robots is based on infrared (IR) or wired links. The disadvantage of these physical layers is that they are not well-matched to module connection and disconnection. The main challenge is that communication links between connected modules must tolerate uncertainty in module alignment. Precise alignment presents a difficulty to connector design, but is a requirement for IR or wired systems. If the precision requirement is relaxed, problems with crosstalk and neighbor detection emerge [2]. Tightly coupling the physical implementation of the communication system with the mechanical design of the connection system increases the difficulty of both problems. We believe this tight coupling is unnecessary.

Our approach is to use wireless RF links as the primary means of communication between connected modules. Radios do not require precise module alignment and can be physically placed inside the module shell. Further, because radios do not require externally exposed components, the communication system can be more robust in outdoor environments. IR or wired links, in contrast, require external components that are susceptible to damage or signal loss from abrasion and dust.

The most obvious implementation of RF communication in a modular robot is an ad-hoc mesh network. However, mesh networks introduce additional challenges. Standard mesh networks act like a communication bus, where nodes cannot transmit in parallel. The seminal paper by Gupta and Kumar [3] shows that the capacity of mesh networks scales by $\theta(\sqrt{n})$ as the number of nodes n

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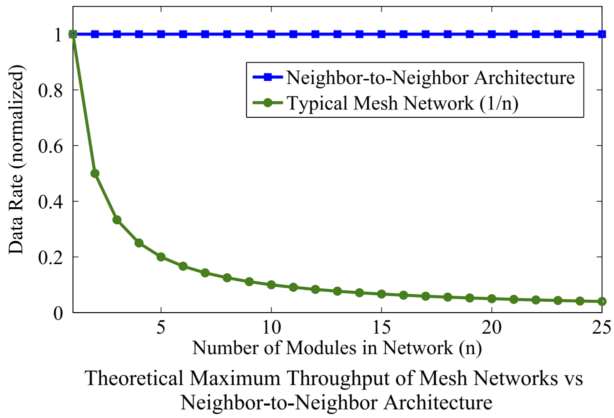

Fig. 1. A comparison of the throughput capacity of a typical wireless mesh network versus our neighbor-to-neighbor architecture.

grows to infinity. This implies that the bandwidth available to each node is $\theta(\sqrt{\frac{1}{n}})$ and hence mesh networks are not suitable for applications with large numbers of nodes. However, this bound does not hold when communication is local [4]. The key insight in the modular robots case is that in implementing decentralized algorithms, communication is predominantly neighbor-to-neighbor.

In previous work, we proposed a new architecture where each communicating node uses multiple radios and multiple channels [5]. A single communication channel can be safely "recycled" assuming a minimum physical separation distance. This threshold is determined analytically for the given radio hardware. The idea is that it is possible to compute a channel assignment that allows all neighbor pairs to communicate using their assigned channel without interference. A special case is when all pairs of radios are above the separation threshold. In this special case, only a single channel is needed.

In this paper,[1] we propose a system based on the multi-radio single-channel case and analytically prove that the architecture scales to an infinite number of radios for two- and three-dimensional network configurations. The performance of the system is also empirically evaluated in a testbed with 15 unactuated modules. The system is benchmarked with synthetic and realistic data loads. Results support our main hypothesis that the performance of our proposed system remains constant as network size increases, whereas capacity in a standard mesh network decays exponentially. This concept is illustrated in Fig. 1.

In addition to scalability validation, we also experimentally validate tolerance to misalignment, hardware support for neighbor detection, and performance in the presence of ambient WiFi emissions. Finally, we show experimentally that our system does not preclude the addition of a separate global communication channel, which would allow intermittent communication between non-connected modules.

The results in this paper establish the feasibility of wireless RF as a primary communication medium for modular robot systems. The significance of these results is to support robust implementation of decentralized algorithms that depend on reliable neighbor-to-neighbor communication. Our results encourage the adoption of wireless RF in future modular robots, and we provide a discussion of implementation issues to assist the designers of such systems.

The remainder of this paper is organized as follows. We present a review of related work in Section 2. In Section 3, we define our multi-radio architecture and prove scalability for infinitely large networks. We present experimental results in hardware that evaluate the raw throughput capacity in Section 4 and performance with a benchmark algorithm in Section 5. In Section 6 we demonstrate automatic neighbor detection and show an extension to the architecture for global communication. Section 7 discusses implementation trade-offs and Section 8 concludes the paper.

2. Related work

The majority of SR robots use IR links [7–16], wired links with physical connections [17–22] or a combination of both [23–26,18] as the main communication medium for planning and control. IR requires line-of-sight and wired connections require modules to be physically docked. Neither is suitable for harsh or outdoor environments where dirt can obstruct and abrade IR optics or jam electrical connectors. IR-based systems are subject to crosstalk [2,27] and care is required to design effective shielding. Wired links with physical connections must be designed as part of the inter-module connector, which further complicates the difficult connector-design problem. Wireless RF systems avoid these issues, which motivates us to investigate this option.

Several modular robot systems use wireless links for a human–robot interface [18,8,7,15,28] but not for inter-module communication. Yim et al. [26] use Bluetooth radios for communication between disconnected modular robots but neighbor-to-neighbor communication between modules is implemented through wired connections and IR. YaMor [29] is the most notable example of RF used for inter-module communication. YaMor uses Bluetooth, a Frequency Hopping Spread Spectrum (FHSS) radio. FHSS radios randomly hop across a large pool of orthogonal channels which allows multiple transmissions to occur simultaneously. Bluetooth uses a master–slave architecture to achieve the tight time synchronization required for channel hopping and to guarantee low latency. However the master–slave architecture makes it cumbersome to deploy Bluetooth in a mesh network topology (as evidenced by the need for a custom Scatternet protocol). Bluetooth is effective in small robots, but faces the same scalability issues as mesh networks when the number of modules approaches the number of orthogonal channels (79).

Wireless modules have also been used for inter-module communication in [30–32]. However these papers only demonstrate a limited number of modules and scalability is not considered.

Gilpin et al. [33] use electro-permanent magnets to provide scalable inter-module communication. When two modules are connected, the magnets communicate with induction at 9600 baud. Module alignment and orientation is still important [33] and modules have to be physically connected.

Cabrera et al. [34] use IEEE 802.15.4 radios for local and global communication. Neighbor detection with the same radios and directional antennas was also demonstrated.

The use of ZigBee radios for SR robots was evaluated in experiments involving 15 ZigBee modules in our earlier work [35]. The results indicated that the use of ZigBee wireless radios is feasible as a limited low-cost communication system for small networks. In this paper we evaluate our architecture using the same benchmark tests and show results for larger network sizes.

There is an immense body of work from the communication community on developing efficient and scalable architectures and protocols for mesh networks [36]. However, to the best of our knowledge, ours is the first paper to specifically address the scalability problem of mesh networks in modular robots.

[1] A preliminary version of this paper appears as [6].