J. Parallel Distrib. Comput. ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

J. Parallel Distrib. Comput.

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

Energy-efficient and delay-aware distributed routing with cooperative transmission for Internet of Things

Shaojie Wen [a,b], Chuanhe Huang [a,b,*], Xi Chen [a,b], Jianhua Ma [c], Naixue Xiong [d], Zongpeng Li [a,b]

[a] State Key Lab of Software Engineering, Computer School, Wuhan University, China
[b] Collaborative Innovation Center of Geospatial Technology, China
[c] School of computer and Information Science, Hosei University, Japan
[d] School of Computer Science, Colorado Technical University, USA

HIGHLIGHTS

- An energy-efficient and delay-aware distributed routing algorithm is proposed for FANETs.
- The dual decomposition technique to transform the centralized problem into distributed problem.
- The network utility, single-hop packet progress are combined with the expected one-hop delay to route the packets.

ARTICLE INFO

Article history:
Received 31 December 2016
Received in revised form 19 July 2017
Accepted 12 August 2017
Available online xxxx

Keywords:
IoT and cyber-enabled applications
Distributed routing
Cooperative transmission
Delay constraint

ABSTRACT

As an important part of IoT, Flying ad hoc networks (FANETs) can provide communication services for different devices in IoT and cyber-enabled applications. However, mobility of unmanned aerial vehicle (UAV) in FANETs results in wireless link unpredictability and increases the complexity of routing algorithms in these applications, especially for real-time routing. In this work, we propose an adaptive distributed routing method with cooperative transmission to effectively solve the problem presented above, in which the transmitters only use local information to transmit packets with help from their cooperative nodes. We formulate a corresponding mathematical optimization problem, in which the objective is to maximize network utility, while keeping end-to-end delay below a prescribed threshold. To support variations in network characteristics and channel states, we estimate the single-hop delay at relay node for each transmission, and use the dual decomposition method to transform the centralized problem into a distributed problem which allows the relay nodes to use only the local channel information and estimated delays to route the packets. Simulation results show that the proposed routing method can improve network performance in terms of energy efficiency, throughput and end-to-end delay.

1. Introduction

IoT and its relevant technologies have started to attract attention from researchers from academia, industry, and government in recent years [20,25]. The development of cyber–physical systems inspires the emergence of IoT and Cyber-enabled applications, and communication represents a major challenge in many of these applications. How to provide better communication service for terminal devices in IoT is a focal point of study in the field. Due to advantages in terms of flexibility and expansibility, single-UAV systems can serve as air cyber-infrastructures to provide an alternative communication means for IoT and Cyber-enabled applications [6]. Unfortunately, the simple functions and limited coverage of single-UAV systems restrict their further applications. Multi-UAV systems are built to improve the operational performance through the cooperation between UAVs. The networks are composed of multiple UAVs, and are known as FANETs, a new use case of mobile ad hoc networks (MANETs). The UAVs can communicate with each other in peer-to-peer mode, hence they can provide the communication services for IoT and Cyber-enabled applications, even if there are no time or resources to create a wired infrastructure. In addition, when the workload of ground networks is high, FANETs can support an immediate communication in multi-hop

* Corresponding author at: State Key Lab of Software Engineering, Computer School, Wuhan University, China.
E-mail addresses: wshaojie@whu.edu.cn (S. Wen), huangch@whu.edu.cn (C. Huang), chenxi_cs@whu.edu.cn (X. Chen), jianhua@hosei.ac.jp (J. Ma), nxiong@coloradotech.edu (N. Xiong), zongpeng@whu.edu.cn (Z. Li).

https://doi.org/10.1016/j.jpdc.2017.08.002
0743-7315/

mode [3] to alleviate the communication pressure of these networks. Although FANETs can effectively expand the service scope of these applications, they introduce new challenges in terms of link unreliability and complex routing algorithm design, especially for real-time routing policy where a selected end-to-end path may become invalid soon.

The topologies of FANETs change dramatically. An established end-to-end path may become unavailable soon due to the disconnected links caused by high mobility of UAVs, hence it is necessary to propose a routing method which not only selects an optimal relay node in distributed manner but also guarantees per-hop transmission reliability. In real-time applications, end-to-end delay is a key criterion to justify whether the transmission tasks are completed or not. Because each packet is appended with a timestamp, the end-to-end transmissions are considered complete if and only if the packets are received by destination correctly within the delay constraint. Nevertheless, it is hard to limit the total transmission delay in a given threshold due to unknown link states in future. Therefore, it is a challenge to design a routing method which can adapt to the time-varying link states and ensure transmission reliability in real-time scenarios.

To solve the link unreliability problem caused by mobility of UAVs and signal interference, cooperative communication (CC) can be carried out between any pair of UAVs with exploiting the broadcast nature of wireless communication, to ensure single-hop reliability [14]. The number of cooperative nodes affects the capability of CC, because more cooperation nodes will consume more network energy and scheduling delay. According to the studies in [30], a single best cooperative node is sufficient to help relay nodes transmit the packets. According to the features of FANETs, it is noted that a centralized routing method is not suitable for the dynamic environment due to the presence of the unpredictable channel states over time. To overcome this obstacle, we transform the centralized problem into a distributed problem using Lagrangian relaxation and dual decomposition, in which the relay nodes only use local link state information and single-hop estimated delay to transmit the packets.

Our contributions are listed as follows:

- We design an optimization framework to mathematically formulate the delay-constrained routing problem, which is proved to be *NP*-hard and difficult to be solved with centralized method due to the fast motion of nodes. Therefore, we use the dual decomposition technique to transform the centralized problem into a distributed problem, in which the transmitters only use local information and single-hop estimated delay to delivery the packet with cooperative transmission.
- We propose an energy efficient and delay-aware distributed routing algorithm, in which the end-to-end delay will meet the delay constraint with high possibility. To maximize network utility and reduce the transmission delay in distributed mode, the network utility is multiplied by the ratio of transmission radius and the single-hop packet progress to obtain the effective network utility. Then we combine effective network utility with expected one-hop delay to determine the relay and cooperation nodes, and reduce one-hop transmission delay.

The remainder of this paper is organized as follows. In Section 2, we introduce previous work related to our studies. In Section 3, we provide the network model and the process of parameter estimation used in this work. In Section 4, we introduce the specific implementation process of the proposed routing algorithms. In Section 5, we show some experiment results of our routing algorithm. Finally, we conclude the paper and discuss future work in Section 6.

2. Related work

There have been a series of studies on the routing problem in IoT and Cyber-enabled applications, Airehrour et al. surveyed secure routing methods for IoT [2]. In this work, we focus on the routing problem of IoT without considering security. Kharkongor et al. proposed a SDN controller with energy-efficient routing for IoT to keep the people connected with 'anything' and 'anyone' and be it 'anywhere' [11]. Their routing protocol considers energy consumption of the various devices, and introduces a SDN controller as a centralized manager for reliable network services. To solve the heavy data transmission causing bottleneck problems in wireless sensor networks, Tseng developed multi-path load balancing routing to substitute Zigbee's AODV routing, which does not consider load balancing for bursty traffic [21]. Nodes can have multiple relay nodes to transmit the data and estimate future load of next-hop by exchanging flow information containing current load.

The routing protocols presented above do not consider the mobility of various devices, when the velocity of devices is high enough, such as in the case of UAV, these protocols cannot function well. Bouaziz et al. considered challenges induced by mobility of devices [3]. A new energy-efficient and mobility aware routing protocol (EC-MRPL) is proposed to eliminate the negative effects caused by the disconnection of nodes and intermittent connectivity. EC-MRPL integrates mobility detection and replacement strategy aware of resource constraints, which can significantly improve network performance in terms of energy and link reliability. Cooperative communication can improve link reliability in mobile environment by exploiting the broadcast nature of wireless communication. Xie et al. studied a joint problem of multi-radio cooperative routing and relay assignment based on the benefits of CC in multi-radio multi-hop wireless networks, and formulate this problem as a mixed-integer programming (MIP) problem. To implete the algorithm in distributed mode, the available link capacity is considered as a parameter of routing metric to find the feasible set of channels [27]. To address the problem that CC can result in severe interference in large networks and even degraded throughput, Xie et al. proposed a solution which simultaneously considers cooperative routing, channel assignment, and relay selection to combat co-channel interference [26]. The contention-aware channel utilization routing metric and traffic aware channel condition metric are proposed to capture interference cost and evaluate the channel load condition.

Along the direction of FANETs, Danil et al. classified the existing routing protocols in FANETs into six major categories, while these protocols are critically analyzed and compared based on various performance criteria [10]. S. Vasiliev et al. investigated throughput efficiencies of relaying algorithms with the ideal selective-repeat ARQ in FANETs [23]. They propose Markov models of three relaying algorithms: chunk-by-chunk algorithm, fifty–fifty algorithm, and ratio-based algorithm and compare throughput efficiencies of these algorithms. Tareque et al. studied new challenges of FANETs as compared to traditional MANETs [9]. They analyze and compare the existing routing protocols for FANETs based on various performance criteria. Multiple token structure has been implemented for UAVs in [22] acting with a dynamic topology, and results show that it enables each node to obtain more accurate position information of other nodes. Rosati et al. proposed predictive OLSR (P-OLSR) which is an OLST extension designed for FANETs, to address the challenge that existing routing protocols designed for MANETs partly fail in tracking network topology changes [19]. P-OLSR computes the relative-speed between two nodes and takes that as a parameter of path metric to help each node make a wise routing decision. The routing algorithms presented above only consider the reachability of transmission and ignore the delay constraint attached to the packets. Li et al. conducted statistical analysis

Please cite this article in press as: S. Wen, et al., Energy-efficient and delay-aware distributed routing with cooperative transmission for Internet of Things, J. Parallel Distrib. Comput. (2017), https://doi.org/10.1016/j.jpdc.2017.08.002.