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Cross-layer topology design for network coding based wireless multicasting

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ABSTRACT

This paper considers wireless multicast networks where network coding (NC) is applied to improve network throughput. A novel joint topology and cross-layer design is proposed to maximise the network throughput subject to various quality-of-service constraints, such as: wireless multicast rate, wireless link capacity, energy supply and network lifetime. Specifically, a heuristic NC-based link-controlled routing tree algorithm is developed to reduce the number of required intermediate nodes. The proposed algorithm facilitates the optimisation of the wireless multicast rate, data flow of wireless links, energy supply and lifetime of nodes through a novel cross-layer design. The proposed joint topology and cross-layer design is evaluated and compared against other schemes from the literature. The results show that the proposed scheme can achieve up to 50% increase in the system throughput when compared to a classic approach.

1. Introduction

In today's environment, wireless multicast networks (WMNs) are facing important challenges as the network performance is highly affected by various dynamics of the wireless links (e.g. limited channel bandwidth, severe power constraint, unstable signals, interferences, etc.). For this reason, multicasting has attracted an increasing interest in wireless communications with extensive investigations [1–6]. With the advances of wireless communications, the demand of high-throughput multicasting is crucial, especially in services which require high-rate multicasting traffic, e.g. telconferencing [5,7] and multimedia streaming [8].

Network coding (NC) is regarded as an effective technique to improve the throughput of a communication system [9,10]. As compared to the conventional store-and-forward manner at intermediate nodes in a multi-hop wireless network (e.g., a WMN), NC has been applied at the intermediate nodes to dramatically improve the throughput of wireless networks [11–13]. By performing algebraic linear/logic operations on received packets at the intermediate nodes with NC techniques, the bandwidth could be saved for a higher system throughput. Many NC-based protocols have been proposed and investigated for multicast channels (e.g. in [4,6]).

In NC-based WMNs, topology design has significant impact on the system throughput [14–19]. In [14], an iterative cross-layer optimisation was proposed to allocate physical and medium access layer resources for network planning. The scheduling for optimising the NC-based multicast was investigated in [15,16]. In [17], the topology was shown to affect the efficiency of NC in improving the system throughput since destination nodes may not receive enough linearly independent NC-based data packets to recover the original data packets. Moreover, the use of all available nodes in WMNs to support the multicasting for a group of destination nodes causes a large increase in energy consumption within the network [18]. In [19], the opportunity and applicability of NC

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in practical wireless networks have been shown to be dependent on the topology design. Therefore, the topology design is a challenging task for NC-based WMNs, especially for multimedia applications which require high multicasting traffic along with high quality-of-service (QoS).

In this paper, we consider a WMN consisting of multiple multicasting sets in which each source node multicasts data to a group of desired destination nodes with the assistance of multiple relay nodes. We jointly exploit the advantages of linear NC techniques and QoS-driven adaptive data streaming in designing a WMN topology that can miximise the system throughput. To the best of our knowledge, existent proposals in the literature (e.g. [14–19]) do not entirely tackle the topology design under the constraints of QoS including multicasting rate, capacity of wireless channels, energy supply, and node/network lifetime. The proposed multicast topology design is a novel cross-layer scheme that investigates wireless multicast characteristics at underlying layers while guaranteeing the end-to-end QoS required by multimedia users. Furthermore, the proposed design makes use of the medium access control (MAC) to allocate the transmission time, energy supply and data rate to a node (e.g. in [20–23]), while the routing is used to determine an effective path for different data flows. The work in this paper is extended from [24]. The main contributions of this paper can be summarised as follows:

- The WMN topology design is formulated as a cross-layer optimisation problem. The objective is to miximise the system throughput over the design metrics including wireless multicasting rate of source nodes, amount of wireless data flows, energy supply at nodes, and lifetime of nodes subject to various QoS constraints on flow conservation, wireless link capacity, wireless multicast traffic rate, node energy, total energy, and network lifetime. This NC topology design problem is shown to be NP-hard in the WMN.
- A heuristic NC-based link-controlled routing tree (NC-LCRT) algorithm is proposed associated to the analysed NP-hard problem to construct a multicasting tree. By referring to the LCRT algorithm [25], the NC-based LCRT algorithm employs a minimal number of nodes for NC operations, as contrast to the design using all nodes in the system.
- Based on the NC-based LCRT algorithm, the cross-layer design, targeting at optimising the wireless multicast rate, data flow of wireless links, energy supply, and nodes' lifetime, are studied. By solving the cross-layer optimisation problem, it is demonstrated that, given fixed lifetime of nodes, the optimisation problem is a linear programming problem and the network lifetime constraint can be relaxed as the lifetime of nodes approaches network lifetime.

The performance of the proposed cross-layer design is evaluated and compared against other solutions from the literature. The results show that the system throughput increases as either total energy available for network increases or network lifetime decreases. Additionally, with linear NC technique, a significantly improved throughput is achieved with the proposed protocol compared to the non-NC-based LCRT protocol, especially with a large wireless multicast set.

The rest of this paper is organised as follows: Section 2 describes the network model of a wireless multicast network and discusses various topology design aspects. The formulation of the cross-layer optimisation problem is presented in Section 3. Sections 4 and 5 present the proposed heuristic NC-based LCRT algorithm and cross-layer design. Numerical results are presented and discussed in Section 6. Finally, Section 7 draws the main conclusions from this paper.

2. Network model and topology design aspects

In this section, we first present the network model under investigation of the paper, and then introduce different aspects in designing multicast topology in WMNs.

2.1. Network model

We consider the scenario in which the number of wireless multicast groups and the members (e.g., sources, destinations) in each group are known. Hence, the network conditions should be unchanged over the time period of the multicasts. As such, our study employs a quasi-static WMN with a set of N nodes (denoted as $\mathcal{N}$) in which each node acts as either a source, or a relay, or a destination. Let the distance and the capacity of the wireless link between two adjacent nodes (say the ith node and the jth node) be $d_{i,j}$ and $C_{i,j}$, respectively, where $\{i, j\} \in \mathcal{N}$. Suppose there are M wireless multicasting groups and $\mathcal{S}_m = \{n_{m,0}, n_{m,1}, \ldots, n_{m,|\mathcal{S}_m|-1}\}$, $m \in \mathcal{M} \triangleq \{1, 2, \ldots, M\}$, represents a subset of nodes in $\mathcal{N}$ that requires to join in the mth group, where $n_{m,0}$ is the source of this group and $n_{m,l}$, $l \in \mathcal{L}_m \triangleq \{1, 2, \ldots, |\mathcal{S}_m| - 1\}$, is a destination of this group. Also, let K_m and B_m denote the number of packets and the size of packets multicasted in the mth group. For simplicity, let us assume $K_m = K$ and $B_m = B$, $\forall m \in \mathcal{M}$.

2.2. Topology design aspects

In NC-based WMNs, the topology design was shown to be crucial for implementing linear NC techniques [19]. In this paper, we consider the following topology design aspects:

2.2.1. Wireless multicast traffic rate

If the transmission rate of wireless multicasting in the mth group is R_m, the multicasting performance is acceptable if $R_m \geq \delta_m$ can always be guaranteed during the communication, where δ_m is the rate for the basic-layer performance rate.

2.2.2. Wireless flow conservation

For an intermediate node on a WMN multi-hop path, the amount of total outgoing wireless multicast traffic should be equal to the amount of total incoming wireless multicast traffic. However, in the case of source or destination nodes, the amounts of incoming traffic and outgoing traffic are different and the difference should be the amount of traffic generated at sources. Therefore, if we let $f_{i,j}^{(n_{m,0}, n_{m,l})}$ be the amount of wireless data flow from source node $n_{m,0}$ ($m \in \mathcal{M}$) to destination node $n_{m,l}$ ($l \in \mathcal{L}_m$) on link $i \to j$ ($\{i, j\} \in \mathcal{N}$),