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XCHARM: A routing protocol for multi-channel wireless mesh networks

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ABSTRACT

Recent experimental results have pointed out the impact of physical layer multi-path fading and co-channel interference as the key factors influencing packet delivery among mesh routers (MRs) in wireless mesh networks. In addition, in a multi-channel environment, there exists significant power spectral overlap among channels used by MRs, leading to adjacent channel interference. In this paper, a cross-layer multi-radio, multi-channel routing protocol, XCHARM, is proposed in which the key contribution is the selection of the next hop, channel and transmission rate based on fading and interference concerns. The key features of our proposed protocol are as follows: (i) Routes are chosen based on the availability of channels that support high data rates, exhibit acceptable interference levels and long term resilience to fading related losses, (ii) The path latency is analytically calculated in advance for the candidate routes, accounting for channel induced errors, link layer contention, forward error correcting (FEC) codes, and the allowed data rates over the chosen channels, (iii) The route maintenance is performed by first attempting to identify and correct the point of failure before undertaking a global recovery action. An extensive performance evaluation, spanning the network, link and physical layers, reveals the benefits of adopting our cross-layer routing solution for wireless mesh networks.

1. Introduction

Wireless mesh networks (WMNs) allow supported mesh clients (MCs) to access the Internet gateway by multi-hop packet forwarding over the mesh routers (MRs) [4]. In this paper, we present XCHARM, a Cross-layer CHannel Adaptive Routing protocol for wireless mesh networks, that jointly addresses the concerns of interference, channel fading and transmission rate selection at the physical layer, and link layer error recovery, to meet the end-to-end user specified constraints.

In order to provide good network coverage and connectivity, the MRs are deployed in overlapping spatial regions, as shown in Fig. 1. The problem of interference due to simultaneous transmissions by other MRs, placed in close proximity of the receiver, has been shown to be a key problem in WMNs [17]. This may be alleviated to an extent by using multiple radios on different channels. However, this multi-channel environment introduces interference due to *spectral leakage* as the channels used by the MRs may not be completely non-overlapping. Due to concurrent transmissions on multiple channels and based on their separation in frequency, an additive effect may be seen in this spectral leakage power. The resulting high interference may render correct packet reception infeasible for the considered link. In such cases, the routing protocol design becomes more involved, as interference prone regions, channel assignment and presence of multiple transceivers must also be considered in the route discovery process.

The physical phenomenon of multi-path fading has been shown to be an important reason for packet loss in WMNs [2]. Fading is mainly caused due to reflections from obstacles in the path between a given source–destination pair and results in a sudden, steep fall in signal strength. A type of fading, classified as *frequency selective*, affects the different frequency components of the signal to varying extents. This is particularly harmful as it requires complex hardware and equalizers rather than network protocol solutions for an acceptable packet reception rate. Thus, the routing protocol should be able to distinguish those channels that are preferable for transmission, and in the absence of any such channel, it should avoid the affected links altogether.

Apart from considering inter-channel interference and channel specific fading, classical routing protocols need further modifications before they can be used in a multi-channel environment. Consider the following case, in which, the route setup is undertaken using a common control channel (CCC) and the shortest path metric is used. In the classical AODV approach [25], the routing paths that deliver the route request message (RREQ) from the source first are selected at the destination. However, the RREQ propagates over the CCC, though the actual path uses entirely different channels for data transfer. Hence, its arrival time on the CCC

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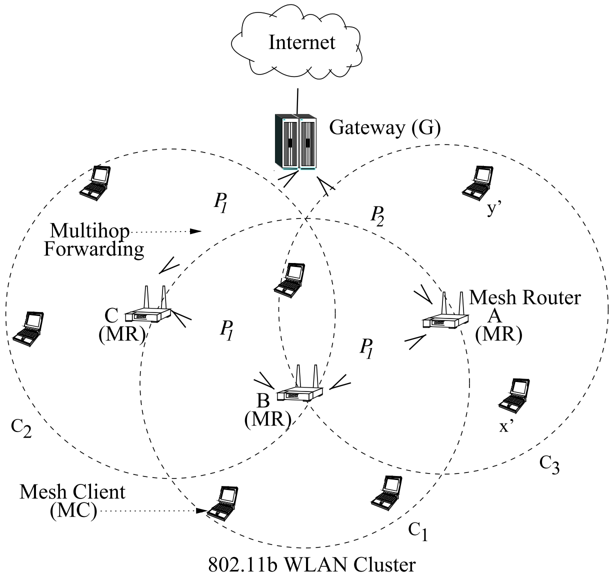

Fig. 1. The mesh network architecture.

is not indicative of the channel quality of the links that form the path. As shown in Fig. 1, the RREQ may arrive at the destination gateway through path P_2 (A-G), earlier than path P_1 (A-B-C-G), as it uses comparatively fewer hops. Thus, path P_2 is chosen over path P_1, without considering the channel quality of the intermediate links that form the paths. A high packet error rate or a low permissible transmission rate, on the chosen channels for any of the links in the path P_2, may offset the advantage of creating shorter routes. There is, hence, a need to adapt the forwarding process of the RREQ, as function of the true channel quality of links that form the routing path. Additionally, several features of the link layer, such as forward error correcting (FEC) code bits, may also affect the data rate for the end-user.

XCHARM has been designed as a distributed routing protocol for WMNs that can address the above concerns by making the following key contributions:

- A interchannel interference model is proposed that accounts for spectral leakage between adjacent channels in a multi-channel scenario. The task of channel selection and estimation of the fading environment is integrated in the proposed routing scheme.
- An analytical expression for the end-to-end latency is derived, that accounts for the error due to the physical environment and link layer decisions of FEC code length.
- A route management functionality is proposed that continuously monitors the performance of the route and initiates local recovery actions by identifying the particular link that causes the bottleneck in the route.

The preliminary findings of this work were published in [8]. In this paper, we have expanded our work significantly by adding an experimental study as motivation, integrating link layer FEC selection, proposing analytical expressions for path latency, enhancing the performance evaluation by comparison with existing schemes, and route management techniques.

The rest of this paper is organized as follows. Section 2 describes the related work and motivates the need for a new cross-layer fading-aware routing scheme. In Section 3, our proposed protocol is described. A thorough performance evaluation is conducted in Section 4. Finally, Section 5 concludes our work.

2. Related work and motivation

In this section, we review cross-layer routing protocols for mesh networks that are chiefly concerned with meeting delay requirements, rather than energy consumption [4].

2.1. Related work

For single channel networks, centralized protocols formulate the task of joint route selection, link level scheduling, and power control [3] as an optimization problem. This can then be solved when the constraints of packet generation at the source and the total traffic arriving at the destination are known [20]. Recently, a routing algorithm considering the network, link and physical layers and also end-to-end constraints is proposed in [10]. However, modeling link access delay is non-trivial. The assumption of the *random link delay* in [10], and the TDMA scheduling in [20] integral to the linear programming formulation, restrict the applicability of such works for practical mesh networks. This limitation is also common to the distributed approaches presented in [16].

Unlike single-channel cross layer protocols discussed above, the use of multiple channels helps in increasing the system throughput by using the available spectrum efficiently. The problem of joint channel assignment and routing based on flow fairness is addressed through centralized approaches, in which, the complete knowledge of the flows between any two MRs is known [5]. Here, a network-wide optimization problem is solved and a constant factor approximation to the optimal solution is provided. These two goals are also considered in the distributed scheme in [19]. When the traffic demands of the flows are not known in advance, an estimation on the mean value and the statistical distribution based on the prior history is undertaken in [14]. A similar joint routing and scheduling approach in [12], lacks physical layer considerations that are present in our work. These works, however, do not scale well with node density owing to the centralized nature of the solution.

In many existing works, distributed routing protocols for multichannels multi-radio WMNs are extensions of classical wireless ad hoc routing schemes [9]. In [26], the Multi-Radio Ad Hoc On-Demand Distance Vector (AODV-MR) is proposed, by extending the popular AODV [25] routing protocol in a multi-radio environment, though the channel selection is performed randomly during the route discovery phase. The Load-Aware Routing Protocol (LMR) [22] extends the AODV-MR [26] scheme with a channel selection scheme which takes into account the traffic load of each channel. Different from these approaches, a mechanism for automatic rate selection and route quality evaluation using statistical information (instead of instantaneous channel measurements) is proposed in [24]. Other recent works tradeoff throughput for interference protection to the flows during path selection [6], while the reverse consideration is present in [15].

In using packet error as the main metric, some links may not be preferred for a route owing to errors caused by reasons such as: contention losses, buffer overflow etc. However, in a cross-layer approach, such as ours, these can be identified and corrective actions can be taken at that specific underlying layer. Instead, we wish to explore certain unique environmental conditions that are out of control of the node (say, reflections that cause frequency selective fading), which have severe and long term impact on routing, and must be avoided right at the onset.

In XCHARM we adopt a cross-layered design which allows to (i) distinguish the type of fading on each link, so that flat-fading links offering high data-rates are preferred (Section III.C) (ii) allocate channels among the flows in a distributed way in order to minimize the interference caused to other MRs transmitting on other