A Fading and Interference Aware Routing Protocol for Multi-Channel Multi-Radio Wireless Mesh Networks

Kaushik Roy Chowdhury
Department of Electrical and Computer Engineering
Northeastern University, Boston, USA
krc@ece.neu.edu

Marco Di Felice
Department of Computer Science
University of Bologna, Italy
difelice@cs.unibo.it

Luciano Bononi
Department of Computer Science
University of Bologna, Italy
bononi@cs.unibo.it

ABSTRACT

Multi-channel Multi-radio technology constitutes a viable approach to expand the capacity of Wireless Mesh Networks (WMNs). While many routing and channel assignment schemes have been proposed for WMNs, it is also important to integrate physical layer considerations into the routing process. In particular, multi-path fading is a challenging physical phenomenon, and it has been shown to be an important reason for packet loss in WMNs. In a multi-channel environment, the problem becomes more involved because different channels may undergo fading to varying extents. In addition there exists significant interference owing to the power leakage between the channels used by adjacent Mesh Routers (MRs). In this paper, we propose a Cross-layer CHannel Adaptive Routing protocol (XCHARM) for Multi-Radio Multi-Channel WMNs. XCHARM integrates routing and channel assignment during route setup, so that the interference caused by nodes transmitting on non-orthogonal channels in the same carrier sensing domain is greatly mitigated. Moreover, it jointly addresses the problems of channel and transmission rate selection based on fading and interference concerns. The simulation results confirm the benefits of the proposed architecture when compared with other routing protocols for WMNs, under realistic channel conditions and different networks topologies.

Categories and Subject Descriptors

C.2.1 [**Computer Communication Networks**]: Network Architecture and Design - Wireless Communication.

General Terms

Performance, Design, Experimentation.

Keywords

Wireless Mesh Networks, Routing Layer, Cross-Layer Design, Multi-Radio technology, Performance Evaluation.

PE-WASUN'09, October 28–29, 2009, Tenerife, Canary Islands, Spain.

1. INTRODUCTION

Wireless Mesh Networks (WMNs) is envisioned as an economically viable networking paradigm to provide broadband Internet access on large residential areas. A typical WMN consists of two types of nodes: mesh clients (MCs) and mesh routers (MRs). MRs form a static backbone, which is responsible for traffic forwarding on behalf of the MCs towards the closest Internet gateway [3]. With advances in multimedia applications and an increased user base, expanding the capacity of WMNs becomes a key research challenge. To this aim, a common approach is to equip each node with multiple, half-duplex radio interfaces, where each interface is tuned on a different channel. This architecture is called Multi-Radio Wireless Mesh Networks (MR-WMNs) [3, 5].
The core functionality of multi-hop WMNs is the routing capability. Despite the availability of several routing protocols for wireless networks, routing protocols for MR-WMNs are still an open research field, mainly due to the challenges which should be jointly addressed in protocol design [4, 8].
In this paper, we present XCHARM, a Cross-layer CHannel Adaptive Routing protocol for MR-WMNs. XCHARM jointly addresses three main challenges of MR-WMNs.
First, in a multi-channel multi-radio environment, the routing protocol should decide (i) the address of the next-hop node and (ii) the radio-interface to be used for each transmission, on each link. Most of the routing schemes for WMNs perform path and channel decisions sequentially, i.e. the channel allocation is first performed and then the best routing paths are identified, according to some kind of routing metrics. The main drawback of this approach is that additional overhead is required to perform channel assignment. Routing and channel assignment should be jointly performed, in order to reduce communication, computation, and storage complexity [4, 6, 8, 9, 11, 17].
Second, although the multi-channel environment may increase the effective network capacity, it may also introduce interference due to *spectral leakage* from the channel used for transmission by neighboring MRs. 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 [1]. The resulting high interference may render correct packet reception infeasible for the considered link. We also emphasize here that the set of interferers might be larger than the 1-hop neighbours, since the carrier sensing range is usually twice the transmitting range [1]. 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.

Third, each channel may experiment different conditions at physical layer. In particular, 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. Fading can be classified into *flat* or *frequency selective* based on the coherence bandwidth (B_c) of the channel [16]. B_c is defined as the approximate maximum bandwidth over which two frequencies of a signal are likely to experience comparable amplitude fading. If the coherence bandwidth of the channel (B_c) is lower than the signal bandwidth, frequency selective fading is observed. This is particularly harmful as various frequency components are affected differently and requires complex hardware, such as RAKE receivers with multiple taps, for correct reception. If B_c is greater than the signal bandwidth, it results in a flat fading channel. Here, the signal experiences fluctuations with time with occasional deep fades, but shows a constant channel gain in the frequency domain. In a multi-channel scenario, different channels may undergo fading to varying extents. 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.

XCHARM has been designed as a distributed routing protocol for WMNs that can address the above concerns and allows for cross-layer interaction. XCHARM combines channel allocation and on-demand route discovery, and jointly addresses the concerns of interference, channel fading and transmission rate selection at the physical layer. The main contributions of our work are as follows:

- A realistic interference model is proposed that accounts for spectral leakage between adjacent channels in a multichannel scenario. Using such model, channel allocation is performed during route setup, in order to (i) reduce the inter-flow and intra-flow interferences and (ii) guarantee an efficient and fair utilization of all the available channels.

- The physical phenomenon of multi-path fading is taken into account during the route setup. For each link, the coherence bandwidth of each channel is estimated, and the transmission rate of each link is adapted so that frequency selective fading is not observed.

- Using the metric based on the fading characteristics of each channel, a novel forwarding mechanism is introduced, so that the path providing the highest allowed transmitting rates is identified.

The rest of this paper is organized as follows. Section II describes the related work and motivates the need for a new cross-layer fading-aware routing scheme. System models and assumptions are collected in Section III. In Section IV, we give a detailed description of the various components of our proposed protocol, XCHARM. A thorough performance evaluation is conducted in Section V. Finally, Section VI concludes our work.

2. RELATED WORKS

Many routing protocols have been proposed for MR-WMNs. 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 [4]. 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 [9], by first exchanging node information and then assigning distinct channels over two hops during the routing process. This method, however, does not scale well with node density and does not involve key physical layer metrics such as transmission rate, power, and channel quality.

In most cases, distributed routing protocols for MR-WMNs are extensions of classical wireless ad hoc routing schemes, for the multi-radio environment [6]. The MR-LQSR protocol [8] uses the Weighted Cumulative Expected Transmission Time (WCETT) metric for multi-radio, multi-channel routing by considering the link loss rate and bandwidth of each link. In [14], the Multi-Radio Ad Hoc On-Demand Distance Vector (AODV-MR) is proposed, by extending the popular AODV [15] routing protocol in a multi-radio environment. When a route is required in AODV-MR, a Route Request message (RREQ) is broadcasted on all the available radio interfaces and received by all the neighbouring nodes. Then, each intermediate node broadcasts the RREQ on all the interfaces except for the one from which the RREQ message was received first. The route discovery process continues until the destination node is reached. In such a case, a Route Reply (RREP) message is sent back to the source and the forward path is established. In AODV-MR [14], the channel selection is performed randomly during the route discovery phase. The Load-Aware Routing Protocol (LMR) [11] extends the AODV-MR [14] scheme with a channel selection scheme which takes into account the traffic load of each channel. Hyacinth [17] is another example of joint channel allocation and routing protocol for MR-WMNs, where the number of interfaces is lower than the number of channels. The routing algorithm works by using a spanning-tree based routing algorithm [17].

Although all the previous schemes combine channel allocation and routing process, they fail in considering physical layer impact on end-to-end performance. Moreover, to the best of our knowledge, the current research in routing solutions for WMNs does not consider, as an integrated solution (i) the co-ordination with multiple radios and channels, (ii) joint optimization of the network-link-PHY layer parameters, such as, transmission rate and channel selection, and (iii) the physical phenomenon of multi-path fading. Our proposed protocol, XCHARM, uses local co-ordination between the MRs and leverages cross-layer information to address the above issues.

3. SYSTEM MODEL AND ASSUMPTIONS

In the remainder of this paper and without any loss in generality, we consider as target scenario a MR-WMN, based on the IEEE 802.11 technology [1]. Several MCs, possibly mobile, may be under the coverage of a stationary MR. The MRs form the wireless backbone for carrying data flows to and from the MCs by multi-hop forwarding to reach the Internet gateway. Each MR is also aware of its own location.

XCHARM provides a solution for the MR-MR routing and is assumed to operate on channels not affected by the MR-MC traffic. We assume that: (i) each node is equipped with M radio interfaces, (ii) the number of interfaces is equal to the number of channels, and (iii) each interface is tuned on a different channel. Moreover, each radio interface implements the basic 802.11 Distributed Coordinated Function (DCF) [1]. In our scheme, the available channels are logically divided into a common control channel (CCC) and M-1 data channels (DCs). CCC is used to transmit routing control messages for route setup and route maintenance (e.g. RREQ and RREP messages). All the available channels are half-duplex, supporting multiple transmission rates, $T_1 < ... < T_\psi$, that require bandwidth $B_1 < ... < B_\psi$ respectively.

4. PROPOSED ARCHITECTURE

4.1 Protocol Overview

XCHARM uses an on-demand routing approach, inspired by the AODV protocol [15]. The route setup phase is comprised of the following three functions: (i) *Channel selection stage*, in which, the MR forwarding the RREQ message and its potential next hops decide on a set of usable channels while accounting for external interference, (ii) *Channel and MR ranking*, that establishes an order of preference in the channels and the candidate forwarding MRs, that are found to be suitable for transmission, (iii) *Defer Timer*, that helps in forming good routes by deferring the forwarding process at the MRs as a function of their ranks.

The route discovery procedure is invoked only when a route between a new source-destination pair should be established. In such a case, the Route Request message (RREQ) is sent out by the source MR on the CCC. In this message, the MR also includes the list of channels that are *favorable* to it. The favorable set of channels is so chosen that the other receivers in its interfering range are not affected when the new path is in use. On this set of channels, the transmitting MR also emits pilot pulses, so that the receiver MRs can estimate the channel quality in terms of channel coherence bandwidth [10]. This RREQ is received by several potential next-hop MRs, which then check their own interference neighborhood to identify a set of mutually acceptable channels, called as the *favorable channel set.* From the receiver's viewpoint, the channels chosen by it should not be susceptible to interference from other transmitters in its carrier sensing domain. Each receiver then proceeds to preferentially order the set of favorable channels, based on the pulse based fading estimation and the maximum allowed transmission rate. We introduce a ranking function that allows the receiver MRs to rank themselves on an absolute scale, based on the best channel that they perceive. This can also be considered as choosing which MR is the most suitable next hop forwarder for the RREQ, as a function of the link channel characteristics. The MRs defer the propagation of the RREQ depending on their ranks, so that the MRs with the best channel quality get transmission priority, at each link. While forwarding the RREQ, the MR also includes in it its own identifier (*id*) and its current location. This process is repeated for the intermediate hops till the destination is discovered. The defer delay assures that the RREQ arriving first at the destination corresponds to the path providing the highest allowed transmitting rates. Then, a Route Reply (RREP) message is sent back to the source. Each node, say MR i, forwarding the RREP message to next-hop node, say MR j, includes in it the channel previously chosen for link i-j. When MR j receives the RREP message, before forwarding it, it sends in broadcast a Channel Confirmation message (CCONF) to inform other neighbouring nodes about the channel allocation. The CCONF message includes: the channel chosen on link i-j, the *id* and location of the transmitter node (i.e. MR j), the *id* and location of the receiver node (i.e. MR i). The CCONF message is received by all the neighbours of MR j, and it is re-broadcasted by other MRs for a maximum number of hops h. In our experiment, we set h equal to 2. In this way, all nodes at 2-hop distance of current receiver/transmitter nodes are informed about the channel allocation performed by MR i and MR j and their locations. The RREP forwarding is continued till the source is discovered. Then, the route is established and can be used to transmit data packets.

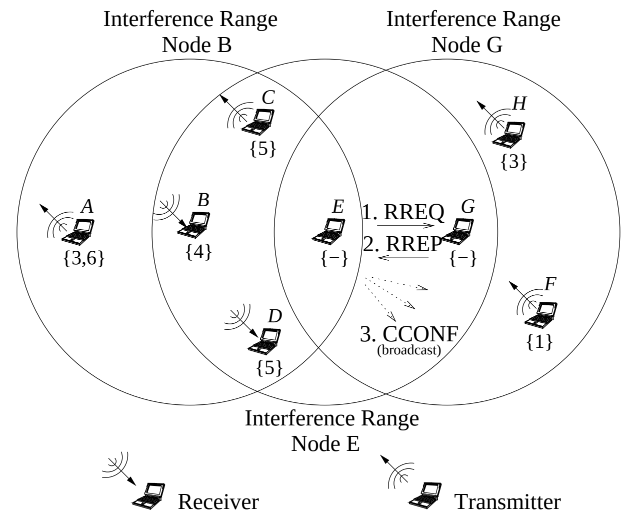

Figure 1: RREQ coverage area and formation of favorable sets at the transmitter and receiver. The channels used by an MR are indicated in the parenthesis.

4.2 Channel Assignment

The main functionality of this stage is to ensure that the sender and receiver MR pair agree on a channel, such that, the effect of external interference on it is minimized. In addition, when this channel is used for transmission, it should not adversely affect the ongoing communication in the neighborhood. We first define our interference model and then propose our channel selection algorithm.

4.2.1 Interference Model

In a multichannel environment, the assumption of strictly non-overlapping channels may not be correct. As an example, significant power leakage between adjacent channels occurs in the IEEE 802.11b systems. Our protocol determines channel availability based on the summation of the individual leakage powers in that channel. We assume a simple free space path loss model and a constant transmit power for all MRs, normalized to 1. Now, the average power, $P_{i,j}(f_i, f_j)$, received on channel f_j at MR j due to transmitter i on channel f_i, when separated by a distance $D_{i,j}$ is given by,

$$P_{i,j}(f_i, f_j) = I(f_i, f_j).\alpha_i D_{i,j}^{-\beta} \quad (1)$$

Here, $\alpha_i = \frac{G_t G_r c^2}{(4\pi f_i)^2}$, where G_t and G_r are the transmit and receiving antenna gains, and c is the speed of light. $I(f_i, f_j)$ is the spectral overlap factor or the leakage power between the channels of transmitter (f_i) and receiver (f_j). This is either made available as standard data based on channel separation or can be calculated through power mask requirements [16].

Our proposed approach allows the MRs to use more than one transceiver for sending and receiving data packets concurrently. However, each transceiver must be tuned to a different half duplex channel. A given MR i maintains a list of channels that it is currently using for data transmission (C_i^T) and reception (C_i^R). Further, let S_i^T and S_i^R represent the MRs within the interfering range of MR i, that are currently receiving and transmitting respectively on at least one channel. S_i^T and S_i^R might include MRs which are in the transmitting range and in the carrier sensing range of MR i. Generally speaking, it might be difficult to build these sets without accurate topology information by each MR. In our solution, S_i^T and S_i^R are dinamically built by MR i, by means of the following messages:

- RRCONF message: each RRCONF message contains a channel allocation (say channel x), the location and *id* of the sender node (say s_C), the location and *id* of the receiver node (say r_C). On receiving the RRCONF message, MR i will include s_C in S_i^T and r_C in R_i^T. Since the RRCONF messages are re-broadcasted by neighbours of current sender and receiver nodes, this means each MR i might take into account channel selection performed by other MRs at 1 and 2 hops of distance, in order to mitigate *inter-flow* interference problems.

- RREQ message: in this case, MR i is aware of previous MRs (e.g. $\{MR_{RREQ}\}$) traversed by the RREQ message. Then, it will include all the nodes belonging to $\{MR_{RREQ}\}$ in S_i^T and R_i^T. This means MR i takes into account channel selection performed by other MRs in the same route, in order to mitigate *intra-flow* interference problems.

4.2.2 Channel Selection

In the overview of our scheme, we used the term *favorable* to describe the set of channels, F_i^T and F_j^R, that may be preferred at the sender, say MR i, and the receiver, say MR j respectively. The set F_j^R is created as a subset of F_i^T, such that there is at least one common channel that is acceptable to both the MRs of a given link. We can formally define these sets as follows:

DEFINITION 1. ***Favorable Transmitter Set (F_i^T)*** *This is a set of channels, such that, when MR i uses any of them for transmission, an acceptable interference power is introduced in the channels used for reception by the other MRs in its interference range.*

DEFINITION 2. ***Favorable Receiver Set (F_j^R)*** *This is a set of channels chosen by the MR j, as a subset of the received set F_i^T, such that, for each channel the total interference is within an acceptable level.*

The word *acceptable* implies that the measured interference power is below a pre-decided threshold necessary for correct packet reception. We next describe how these sets are constructed and their role in the interference management of a link. A given MR j experiences a finite amount of total interference power, $P_j^I(f_j)$ on each of these channels $f_j \in C_j^R$ due to spectral leakage from all the transmitting MRs, S_j^T, in the vicinity. The total interference on a channel f_j, $P_j^I(f_j)$, can be expressed using equation 1,

$$P_j^I(f_j) = \sum_{\forall k \in S_j^T, f_k \in C_k^T} P_{k,j}(f_k, f_j) \quad (2)$$

Thus, from Figure 1, B receives a finite interference power on channel 4 given by $P_B^I(4) = P_{A,B}(3,4) + P_{A,B}(6,4) + P_{C,B}(5,4)$.

When the MR i forwards an RREQ, it first creates its favorable set F_i^T. The transmitted power on any channel $f_j \in F_i^T$ adds to the interference in the channels used by a neighboring MR j for reception (C_j^R). This additional injected power should not cause the interference level to rise higher than the allowed threshold P_{Th}. This condition is checked for all the active receivers in the transmission range of i, i.e. $j \in S_i^R$. Using equation 2, we can formally express the favorable transmitter set, F_i^T as,

$$F_i^T = \{f_i | P_{i,j}(f_i, f_j) < P^{Th} - P_j^I(f_j),\ \forall j \in S_i^R, f_j \in C_j^R\} \quad (3)$$

From Figure 1, MR E is in the process of forwarding the RREQ and must create the set F_E^T. Active receivers in its range are $R_E = \{B, D\}$ and the respective reception channel sets are $C_B^R = \{4\}$ and $C_D^R = \{5\}$, respectively. MR E may include the channel 7 in F_E^T only if the conditions $P_{E,B}(7,4) < P^{Th} - P_B^I(4)$ and $P_{E,D}(7,5) < P^{Th} - P_D^I(5)$ are satisfied.

On receiving the set of favorable channels (F_i^T) from the transmitting MR i, the candidate next hop MRs form their favorable receiver set (F^R) which, by Definition 2, is acceptable to both the sender and receiver on the link:

$$F_j^R = \left\{ f_j | \sum_{\forall k \in S_j^T, f_k \in C_k^T} P_{k,j}(f_k, f_j) < P_{Th},\ f_j \in F_i^T \right\} \quad (4)$$

In our example, we assume that MR G received an RREQ from E, containing $F_E^T = \{2, 7\}$. The active transmitters in its range form the set, $S_G^T = \{F, H\}$. The channel 2 may not be chosen by MR G, as it may see large spectral leakage from the adjacent channels 1 and 3 used by MRs in its vicinity. Noting that $F_G^R \subseteq F_E^T$, if channel 7 has an aggregate interference power less than the threshold, i.e., $P_{F,G}(1,7) + P_{H,G}(3,7) < P_{Th}$, then $7 \in F_G^R$.

It is possible that no mutually acceptable channel is found for a given pair of MRs, e.g. MR i and MR j. Thus, if $F_j^T = \phi$ or a non-empty favorable set at the transmitter gives $F_j^R = \phi$ at the receiver, it implies that the interference on the link, or caused by it, is unacceptable. In this case, the channel with the lowest number of transmitting neighbors (S_j^T) is chosen by the receiver MR j. The node MR j, however, flags this condition and imposes a stiff forwarding penalty on itself, as we shall see in Section 4.3.2. This discourages the route formed from using one of these affected links, unless that is the only option at the destination.

In the general case, the RREQ is received by several candidate forwarders, each having more than one suitable channels for the link. In the next step, we introduce a *ranking* concept that helps in choosing, a particular channel and the MR that shall forward the RREQ earlier than the others. This procedure also accounts for channel fading and biases the formation of routes with better quality links.

4.3 Channel and MR Ranking

We recall that the MR i that forwards the RREQ, also sends out pilot pulses in the channels of its favorable set F_i^T. A ranking concept is then devised based on the maximum allowed transmission rate of a channel that can be supported in the fading environment.

4.3.1 Fading and Rate Estimation

The fading estimate of a given channel $f_j \in F_j^R$ is obtained by the receiver MR j, by measuring the delay spread of the arrival times of the pilot pulses. This delay spread is inverted to get the coherence bandwidth ($B_c^{f_j}$), for each channel f_j in the favorable receiver set [10]. Though such approaches are already used for OFDM channel estimation [12], our protocol only needs to distinguish between flat and frequency selective conditions, making the task simpler than exact channel fading estimation. Also, we recall that $B_1, \dots B_\psi$ are the different signal bandwidth possible, each B_k resulting in a maximum transmission rate T_k. We next order the channels and the MRs based on these maximum allowed transmission rate.

4.3.2 Rank Assignment

The rank of a given channel is defined formally as:

Definition 3. ***Channel Rank*** **($r_{ij}^{ch}(f_j)$)** *For the transmitter-receiver pair $i - j$, this is the index k of the the highest transmission rate for transmitter i allowed by the receiver j, T_k, such that the channel f_j is flat fading.*

Thus,

$$r_{ij}^{ch}(f_j) = \arg_k \max \left[T_k | B_k < B_c^{f_j} \right] \quad (5)$$

We recall that, if the coherence bandwidth of the channel ($B_c^{f_j}$) is greater than the bandwidth used for the signal (B_k), then the channel is flat fading. Thus equation 5 attempts to find out that flat fading channel ($B_k < B_c^{f_j}$) in the favorable set of the receiver, such that the highest possible transmission rate (T_k) is supported. The channel rank $r_{ij}^{ch}(f_j)$ takes the index of this maximum possible rate, for a given channel $f_j \in F_j^R$.

From Section 3, if the order relation between the signal bandwidths and channel coherence bandwidth is $B_1 < B_2 < B_c^{f_j} < B_3 < \cdots < B_\psi$, then the channel f_j is flat fading for B_1 and B_2, but frequency selective for the rest. Hence, if this channel is chosen for the link between two MRs, the transmission rate at the previous hop i must be T_2 (based on the condition $B_2 < B_c^{f_j} < B_3$). This gives the highest allowed transmission rate ($T_{max}^{f_j}$) on channel f_j while keeping the flat fading characteristics. Thus, the channel rank $r_{ij}^{ch}(f_j) = 2$, as $T_{max}^{f_j} = T_2$.

On similar lines, we define the MR rank as:

Definition 4. ***MR Rank*** **(r_{ij}^{MR})** *For the transmitter-receiver pair $i - j$, the rank of the potential next hop MR j is the maximum channel rank over all the channels f_j in its favorable receiver set, F_j^R.*

Thus,

$$r_{ij}^{MR} = \max\{r_{ij}^{ch}(f_j), \forall f_j \in F_j^R\} \quad (6)$$

The rank of a MR helps in classifying the potential next-hops based on (i) whether the channel is feasible for transmission based on fading, and (ii) the maximum transmission rate that is possible on that channel. We next introduce a forwarding delay through a defer timer (DF) based on MR ranks. Here, the MR with the smaller rank will defer its forwarding of the RREQ for a longer time as compared to the MR with the higher rank. Thus, this allows the path information formed by higher ranked MRs to be received earlier at the destination.

4.4 Defer Timer

Let the maximum time that an MR can defer forwarding the RREQ be the system parameter T_{max}^{def}. As the MR rank can take $\psi + 1$ values from $0, \dots, \psi$, we divide this interval into $\psi + 1$ sub-intervals, each of duration $\frac{T_{max}^{def}}{(\psi+1)}$ units. An MR j defers the RREQ received from a sender, say i, for a duration that is an integral multiple of this unit. Intuitively, in the candidate set of forwarders j and l, if MR j has the highest possible rank ($r_{ij}^{MR} = \psi$), it should have minimum forwarding delay. On the other hand, if MR l has only frequency selective channels ($r_{il}^{MR} = 0$), then it should not be preferred as the next hop, and must defer for the longest time. This behavior is captured by the following defer timer that returns the total delay F_{ij} towards forwarding the RREQ received from MR i at MR j,

$$F_{ij} = \left\{ \frac{T_{max}^{def}}{(1+\psi)} \cdot (\psi - r_{ij}^{MR}) \right\} \cdot \kappa \quad (7)$$

where,

$$\kappa = \begin{cases} 1+\psi & \text{if } F_j^R = \phi \\ 1 & \text{otherwise} \end{cases}$$

In the above expression, κ is a weighting factor that is decided on the basis of the feasible receiver set, F_j^R. If at least one mutually acceptable channel is found, $\kappa = 1$. This ensures that the forwarding delay at the MR j is purely a function of its channel ranks (and hence the fading environment). However, if no common channel exists between the sender and receiver, given by $F_j^R = \phi$, any one channel may be chosen by the receiver (from Section 4.2.2). In this case, the forwarding delay at the MR j is significantly increased, to a multiple of the maximum deferring time T_{max}^{def}, by the factor $\kappa = (1 + \psi)$. Thus, routes that pass through this link may be formed with the least priority.

In the example above, MR j, with a better channel between itself and MR i, can immediately forward the RREQ packet to its link layer buffer as $F_{ij} = 0$. Conversely, MR l must wait for the duration of $F_{il} = \frac{\psi . T_{max}^{def}}{(\psi+1)}$ units.

5. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the XCHARM architecture, under different channel conditions and network

Number of nodes	50
Simulation Area	$1000 \times 1000m^2$
Data Packet Size	1000 Byte
Traffic Type	(UDP-CBR)
Radio Interfaces	11
Available channels	11
Transmission Range	250m
Carrier Sensing Range	500m

Table 1: XCHARM Simulation Parameters

loads. We first describe the basic simulation setup in Section 5.1. Sections 5.2 and 5.3 study the benefits of the channel selection scheme and the improvement obtained with the rank-based forwarding respectively.

5.1 Simulation Setup

XCHARM is implemented in NS-2 simulator [13], by first extending it to a multi-radio, multi-channel environment. A multi-path Rayleigh environment was setup in MATLAB and imported for each random node topology used for simulation. We modified the physical layer in NS-2 by incorporating the spectral leakage power and the error caused due to fading. The spectral overlap factor for IEEE 802.11b is given in [7]. We adapted the IEEE802.11b link layer to allow $\psi = 4$ different transmission rates (also channel/MR ranks), $1, 2, 5$ and $10\,$Mbps respectively. Unless stated otherwise, the simulation parameters are reported in Table 1

We considered *random topology* WMNs as reference scenarios, in which 50 MRs are uniformly distributed in a simulated area of $1000 \times 1000m^2$. Source and destination nodes are randomly chosen among the MRs. Each simulation run has been repeated 40 times to get a good statistical relevance. Monitored performance are defined in the following:

- *End-to-end Goodput*, accounts for packets successfully delivered at the gateway node.
- *End-to-end Delay* is the total network delay experienced by data packets from their transmission time at the source node to their arrival at the gateway node.
- *Packet Delivery Ratio* (PDR) is the percentage of successfully delivered packets at the gateway node.
- *Routing Overhead* represents the transmission rate of routing control packets (e.g. RREQs, RREPs, CCONFs) required to setup a route.

5.2 Effect of Channel Selection

In order to evaluate the interference-based channel selection scheme proposed in Section 4.2.2, the effects of the channel ranking mechanism, and the transmit rate adaptation are disabled. The MRs transmit at a fixed rate of 2 Mbps. We compare the performance of XCHARM with those of two other routing schemes for WMNs:

1. AODV: The single-radio single-channel routing algorithm proposed in [15] is evaluated. One route is discovered and utilized for data packets transmission.
2. AODV-MR: The multi-radio multi-channel extension of AODV proposed in [14] is evaluated. Channel allocation is performed during the route discovery phase.

In Figure 2(a), 2(b) and 2(c) we show the performance results of the three protocols in a scenario with 3 active connections, where we vary the connection load produced by each connection (from 150 Kb/s up to 1 Mb/s). Figure 2(a) shows the average end-to-end goodput in such a scenario. From Figure 2(a), we can see that the AODV routing protocol is able to deliver a goodput lower than 200 Kbps; this limitation is caused by the single-radio architecture. AODV-MR enhances the performance of AODV due to the concurrent utilization of multiple channels. However, AODV-MR performs random channel allocation and and does not keep into account spectral leakage inference caused by MRs which transmit on non-orthogonal channels. Differently, the XCHARM architecture takes into account spectrum leakage and interference caused by nodes in the carrier-sensing of current transmitters/receivers. As a result, XCHARM provides a considerable performance improvement under high connection loads (e.g. $\geq$ than 400 Kb/s). The ability of our scheme to maximize channel re-use and to reduce inter-flows interference is also confirmed by Figure 2(b), where the packet delivery ratio (PDR) is shown. From Figure 2(b), we can appreciate that XCHARM produces an effective enhancement of the AODV and AODV-MR performance under heavy traffic load conditions. Figure 2(c) shows the average end-to-end delay for the three protocols, in the same scenario. Figure 2(c) confirms that the XCHARM architecture is able to reduce the end-to-end delay, in all the traffic load configurations.

In Figure 3(a), 3(b) and 3(c) we show the performance results of the three protocols in a scenario where we varied the number of active connections. Each connection transmits data with a constant rate (e.g. 500 Kb/s). Figure 3(a) shows the average end-to-end goodput in such a scenario. When more flows are added in the network, the average contention of each channel increases, due to interference caused by nodes using that channel and to spectral leakage caused by nodes using adjacent channels, according to the spectral overlap factor [7]. The single-channel AODV gets saturated first. AODV-MR enhances AODV due to the concurrent utilization of multiple channels, but also suffers of interference caused by nodes transmitting in the same channel or in adjacent channels, in the carrier sensing of the receiver MR. The XCHARM architecture obtains a goodput performance substantially higher than AODV and AODV-MR in the considered scenario. The same improvement can be seen in terms of end-to-end delay, which is shown in Figure 3(b). Figure 3(c) shows the routing overhead for path setup. As expected, AODV requires the lowest routing overhead rate. Compared to AODV, the XCHARM protocol introduces additional overhead, caused by: (i) the multi-hop forwarding of CCONF messages and (ii) the additional information conveyed by RREQ messages. However, Figure 3(c) shows that such an additional overhead is still lower than the overhead experienced by AODV-MR, where each RREQ message is re-broadcasted on all the available radio interfaces.

5.3 Effect of MR Ranking and Initiative

The MR ranking and initiative concept, described in Section 4.3, allows paths with better channel conditions to forward the RREQ over the CCC earlier by the use of a defer timer (DT). We measure the performance improvement in three different XCHARM configurations, by using the channel rank (CR) scheme in conjunction with the DF:

- XCHARM (CR=off, DT=off): the resulting scheme neither accounts for channel interference (as CR=off) nor the fading environment (and hence the transmission rate) (as DT=off). However, we incorporate the automatic rate selection (ARS) scheme at the link layer to provide a packet error recovery mechanism typically used in commercial IEEE 802.11b systems [1].

- XCHARM (CR=on, DT=off): the ranking scheme described in Section 4.3 is used, but without introducing the defer delay on RREQs based on channel rank (Section 4.4).

- XCHARM (CR=on, DT=on): the full XCHARM scheme is implemented, with the channel ranking and the defer timer mechanisms always enabled.

We observe, from Figure 4(a), that the path formed by the full configuration (CR=on, DT=on) experiences about half the end-to-end delay as the one with the DT disabled, and this difference increases with the number of flows. The configuration with CR disabled experiences the highest end-to-end delay, caused by packet retransmissions at MAC Layer on links affected by frequency selective fading. When the CR scheme is enabled, the rate on each link is adapted not to incur in frequency selective fading problems. Moreover, when the DT is enabled, the path with the higher allowed transmission rates (based on fading) delivers the RREQs message earlier than the other paths, and thus is chosen at the destination MR, producing the improvement on end-to-end delay shown in Figure 4(a). The quality of the chosen path can be measured by the packet delivery ratio (PDR), as shown in Figure 4(b). Although all three configurations experience a drop in the PDR with increased network load, not considering fading may result in a considerable poor performance, as is seen for the case (CR=off, DT=off). Figure 4(c) shows the improvements introduced by the full XCHARM configuration in terms of end-to-end goodput.

6. CONCLUSIONS

In this paper, we have presented XCHARM, a multi-channel, multi-radio cross-layer routing protocol for WMNs. The proposed protocol jointly performs route discovery and channel assignment, in order to provide best reuse of the available channel resources. To this aim, a realistic interference model is proposed that accounts for (i) spectral leakage between adjacent channels in a multichannel scenario, and (ii) interference caused by neighbors at more than 1 hop of distance. Moreover, we have proposed a cross-layer optimization which takes into account the physical phenomenon of multi-path fading during the route setup. Simulation results have shown a performance improvement as we evaluated incrementally the effect of the different constituent blocks of our protocol. We plan to extend this work by considering more general traffic scenarios and incorporating other physical layer features, such as, power control and modulation.

6.1 Acknowledgments

This work is supported by Italian MIUR funds (project PRIN-2006 NADIR: Design and analysis of distributed, and QoS-aware protocols and algorithms for Wireless Mesh Networks).

7. REFERENCES

[1] *IEEE 802.11 WG, IEEE Std. 802.11, 1999 ed, Part II: Wireless LAN MAC and PHY layer specs. 1999.*

[2] D. Aguayo, J. Bicket, S. Biswas, G. Judd, and R. Morris. Link-level Measurements from an 802.11b Mesh Network. In *Proc. of ACM SIGCOMM*, pp. 121–132, Portland, Oregon, USA, 2005.

[3] I. F. Akyildiz, X. Wang, and W. Wang. Wireless Mesh Networks: A Survey. *Elsevier Computer Networks Journal*, 47(4):445–487, 2005.

[4] M. Alicherry, R. Bhatia, and L. Li. Joint Channel Assignment and Routing for Throughput Optimization in Multi-radio Wireless Mesh Networks. In *Proc. of ACM MobiCom*, pp. 58–72, Cologne, Germany, 2005.

[5] L. Bononi, M. Di Felice, A. Molinaro and S. Pizzi. A Cross-Layer Architecture for Effective Channel Assignment with Load-Balancing in Multi-Radio Multi-Path Wireless Mesh Networks To appear in *Wiley's International Journal of Communication Systems (IJCS)*, 2009.

[6] M. E. Campista, P. M. Esposito et al. Routing Metrics and Protocols for Wireless Mesh Networks. *IEEE Network*, 26(1):22(1): 6-12, 2008.

[7] K. R. Chowdhury and I. F. Akyildiz Cognitive Wireless Mesh Networks with Dynamic Spectrum Access. *IEEE Journal on Sel. Areas of Comm.*, 26(1):168–181, 2008.

[8] R. Draves, J. Padhye, and B. Zill. Routing in Multi-radio, Multi-hop Wireless Mesh Networks In *Proc. of ACM MobiCom.*, pages 114–128, Philadelphia, PA, USA, 2006.

[9] M. X. Gong, S. F. Midkiff, and S. Mao. A Cross-layer Approach to Channel Assignment in Wireless Ad hoc Networks. *Mobile Netw. Appl.*, 12(1):43–56, 2007.

[10] A. H. Kemp and E. B. Bryant. Channel Sounding of Industrial Sites in the 2.4 GHz ISM Band. *Wireless Personal Comm.*, 31(3-4):235–248, 2004.

[11] A. N. Le, D.W. Kum and Y.Z. Cho. Load-aware Routing Protocol for Multi-radio Wireless Mesh Networks. In *Proc. of IEEE ICCE*, pages 138–143, San Diego, USA, 2006.

[12] R. Negi and J. Cioffi. Pilot tone selection for channel estimation in a mobile OFDM system. *IEEE Trans. On Consumer Electronics*, 44(3):1122–1128, 1998.

[13] *Network Simulator (NS), www.isi.edu/nsnam/ns.*

[14] A. A. Pirzada, M. Portmann and J. Indulska. Evaluation of Multi-Radio Extensions to AODV for Wireless Mesh Networks. In *Proc. of ACM MobiWac*, pp. 45–51, Torremolinos, Spain, 2006.

[15] C. E. Perkins and E. M. Belding-Royer. Ad Hoc On Demand Distance Vector (AODV) Routing In *Proc. of IEEE WMCSA.*, pp. 90–100, New-Orleans, USA, 1999.

[16] J. Proakis. *Digital Communications.* McGraw-Hill Science/Engineering/Math, August 2000.

[17] A. Raniwala and T.C. Chiueh. Architecture and Algorithms for an 802.11-based Multi-Channel Wireless Mesh Network In *Proc. of IEEE Infocom.*, pp. 2223–2234, Miami, USA, 2005.

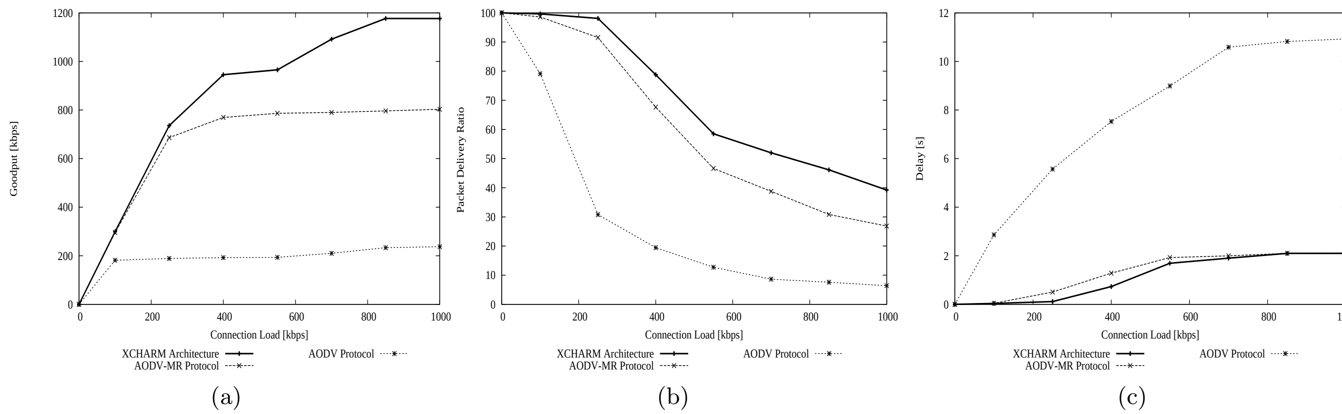

Figure 2: Channel Selection Analysis, Variable Connection Rate: (a) End-to-End Goodput, (b) Packet Delivery Ratio (PDR), (c) End-to-End Delay

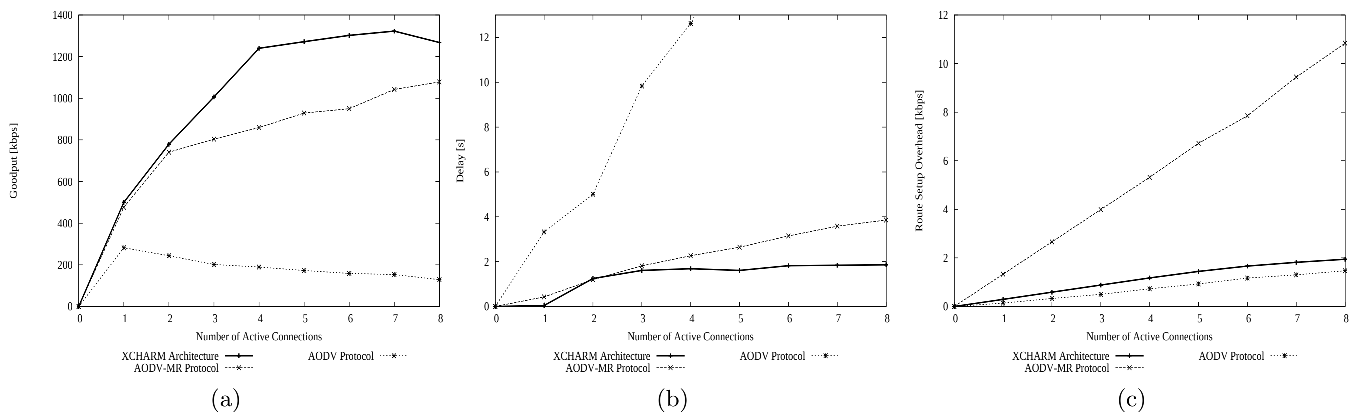

Figure 3: Channel Selection Analysis, Variable Number of Active Connections: (a) End-to-End Goodput, (b) End-to-End Delay, (c) Route Setup Overhead Rate

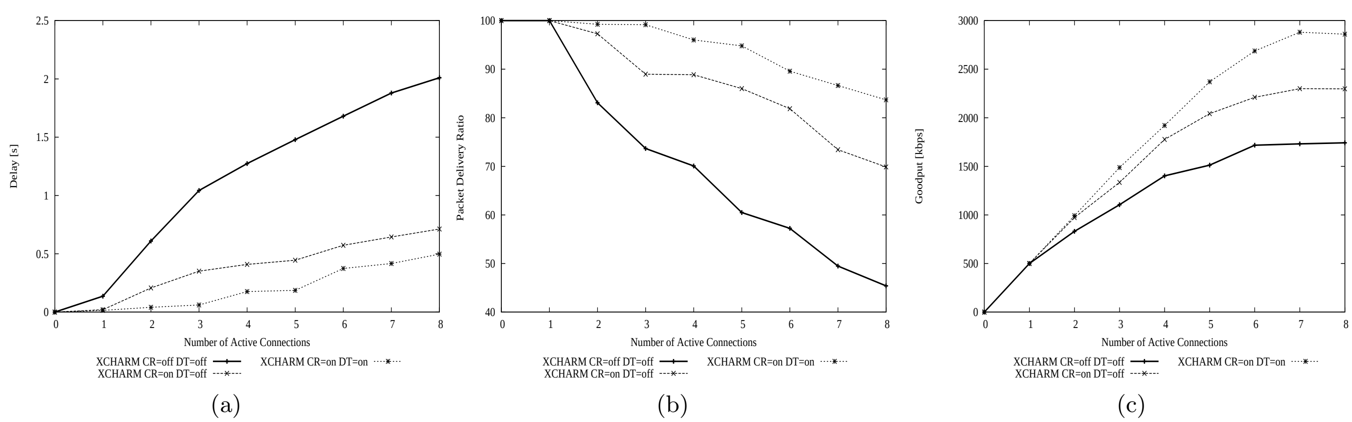

Figure 4: Effect of MR Ranking and Initiative, Variable Number of Active Connections: (a) End-to-End Delay, (b) Packet Delivery Ratio (PDR), (c) End-to-End Goodput