Multi-Radio Hybrid Wireless-Optical Broadband Access Networks

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Abstract — **The wireless-optical broadband-access network (WOBAN) architecture has been proposed as a flexible solution to meet the ever-demanding needs in access networks. At the wireless front-end multi-channel communication, with routers having multiple radio interfaces tuned to non-overlapping channels, can be used to improve network throughput in a cost-effective way. In this paper we address integrated routing and channel assignment in multi-radio WOBANs. Our goal is to evaluate how equipping mesh routers with multiple radios can effectively alleviate the capacity problem in WOBANs. The optimal distribution of radios is also analyzed.**

I. Introduction

Optical and wireless networks were initially developed for different communication scenarios [1]. Optical networks have been mainly used for high-bandwidth and long-distance communications while the wireless technology is used at wireless local networks with flexibility and low bandwidth needs. The present growing demand for bandwidth-intensive services, and the way people now communicate, are accelerating research on efficient and cost-effective access infrastructures whereas optical-wireless combinations are seen as promising approaches. The wireless-optical broadband-access network (WOBAN) architecture has been recently proposed as a flexible solution to meet such ever-demanding needs in access networks [2,3,4]. The WOBAN architecture provides a flexible and cost-effective solution where fiber is provided as far as possible from the central office (CO) to the end users and then wireless access is provided at the front end. Because of such excellent compromise early versions are being deployed as municipal access solutions to eliminate the need for wired connection to every customer's wireless router thus saving on network deployment cost [5].

The network scalability is a very challenging issue in WOBAN architectures [1]. An increase in the number of wireless mesh routers may lead to more hops, decreasing the per router throughput and degradating the performance of the network. A way to reduce degradation is to either use more radio interfaces per router, tuned to non-overlapping channels, or to properly scale the number of gateway routers to that of the mesh routers. Multi-channel communication in wireless mesh networks with routers having multiple radio interfaces are attracting the research community due to the considerable improvement in network throughput and availability of cost-effective wireless devices [6]. Current IEEE 802.11b/g and 802.11a standards, for example, provide 3 and 12 orthogonal channels, respectively, that can work simultaneously with negligible inter-channel interference [7]. Although equipping mesh routers with multiple radios can alleviate the capacity problem, channel assignment to radios becomes a challenge. As far as known, research efforts in WOBAN architectures do not consider multi-radio routers in the sense that the assignment of channels to routers is not considered.

In this paper we address integrated routing and channel assignment in multi-radio WOBANs. Our goal is to evaluate how equipping mesh routers with multiple radios can effectively alleviate the capacity problem in WOBANs. The optimal distribution of radios is also analyzed.

The rest of this paper is organized as follows. Section II provides an overview on WOBAN architectures and multi-radio wireless mesh front-end. Section III defines and mathematically formulates the multi-radio WOBAN problem being addressed in the paper. Section IV analyses results while Section V concludes the article.

II. WOBAN Architecture

At the front end a WOBAN consists of a multi-hop wireless mesh network while at the back end an optical access network provides connection to the Internet [2,4]. At the back end the dominant technology is the passive optical network (PON) having optical line terminals (OLTs), located at the CO, and optical network units (ONUs) to provide connection to wireless gateway routers. Different PON segments are supported, with each segment radiating from a single OLT at the CO to multiple ONUs near end-users. The PON interior elements are basically passive combiners, couplers and splitters. Since no active elements exists between the OLTs and the ONUs the PONs are considered robust networks. In traditional time-division-multiplexed (TDM) PONs an upstream and a downstream wavelength channel is used for bidirectional communication [3]. The WOBAN architecture is illustrated in Figure 1. To provide connection between PONs a reconfigurable optical backhaul, allowing easy bandwidth reallocation, can be used. In [1] a reconfigurable optical ring is proposed.

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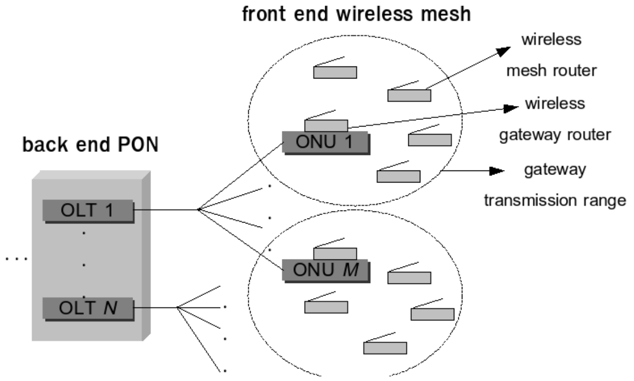

Fig. 1. WOBAN Architecture.

Although having low installation and maintenance cost, due to the passive infrastructure, in the traditional PON the OC is shared by all end users. That is, a packet sent to a specific user, connected to a particular ONU, is broadcast to all ONUs. As users demand for more bandwidth, wavelength-division-multiplexing (WDM) PONs may become a better alternative. A WDM PON solution supports multiple wavelengths over the same fiber infrastructure, but active components become necessary. Incorporating WDM in a PON allows the support of much higher bandwidth and scalability when compared to the standard PON which operates in single-wavelength mode.

Regarding the wireless infrastructure, standard WiFi or WiMAX technology can be used for wireless mesh connectivity. These wireless access technologies have been employed worldwide. Several wireless routers, also called base stations (BSs), provide multihop connectivity for user traffic delivery toward a few wireless gateway routers that are connected to the ONUs of the optical back end. An ONU can drive multiple gateways. An individual user scattered over such geographical area will associate with a nearby wireless router for Internet access. When multiple routers are available the less overloaded one can be chosen. A mesh router can gain access to a gateway router through multiple paths. In the upstream direction traffic can be delivered to any of the gateways while in the downstream direction traffic is sent to a specific wireless router. Note that the gateways/ONUs can be strategically placed over the geographical region to better serve the wireless community [8].

WOBAN is envisioned primarily for residential and business users in municipal networks where wireless devices have limited mobility [2,4]. In this case the location of wireless mesh routers and gateways/ONUs is known in advance and the channel of operation for access points can be carefully planned. Access solutions using WOBAN are expected in many cities around the world in a near future. For a clear understanding of WOBAN advantages see [3].

A. Multi-Radio Wireless Front-End

As previously stated, multi-channel communication in wireless mesh networks with routers having multiple radio interfaces are attracting the research community due to the considerable improvement in network throughput [6]. Current IEEE 802.11b/g and 802.11a standards provide 3 and 12 orthogonal channels, respectively, that can work simultaneously with negligible inter-channel interference [7]. In such multi-radio networks each radio interface has the capability of switching over orthogonal channels and transmission or reception is possible at any channel at a time. That is, considering a specific channel, only links that are located out of their mutual interference range can transmit at the same time. Consequently, a careful channel assignment becomes critical in such networks so that more simultaneous transmission occurs, leading to a global system capacity improvement.

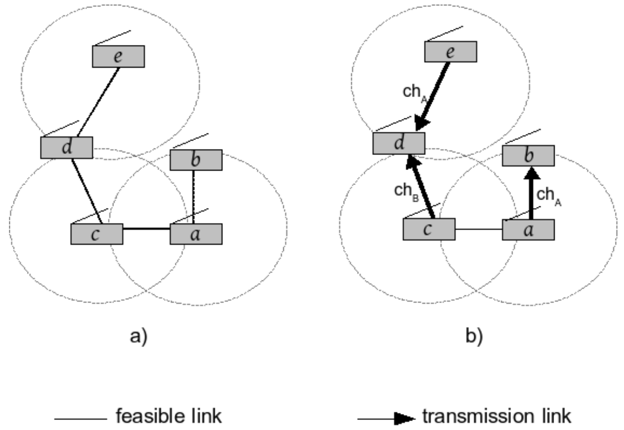

Fig. 2. Illustration of interference in wireless front-end: a) Network with feasible links based on interference ranges; b) Network with transmission links after channel assignment.

To better illustrate interference consider a wireless network modeled by a directed graph $G = (V, E)$, where V is the set of nodes, each equipped with one or more interface cards (referred here as radios), and E is the set of feasible transmission links. A node u can transmit to node v only if the distance between u and v, denoted by $d_{u,v}$, is smaller than the transmission range of node u, denoted by T_u. That is, a feasible transmission link $l \in E : s(l) = u$ and $d(l) = v$ exists if and only if $d_{u,v} \leq T_u$, where $s(l)$ and $d(l)$ are the source and destination nodes of link l, respectively. Feasible transmission links are illustrated in Figure 2a) for an example network. Feasible transmission links are potential transmission links and can become one after a channel being assigned to it for transmission to occur, illustrated in Figure 2b).

While the transmission range of a node, T_u, defines the maximum physical range of a radio signal, the interference range determines the area in which other nodes will not be able to receive or transmit signals successfully. Thus, since G is a directed graph, if we consider a specific link $l \in E$ then another link $l' \in E$ can interfere with l, unable to transmit on the same channel simultaneously, if and only if node $x = s(l')$ or node $y = d(l')$ are located in the interference range of node $u = s(l)$, i.e.

$$d_{u,x} < (1 + \delta) \times T_u \text{ or } d_{u,y} < (1 + \delta) \times T_u \quad (1)$$

where $\delta \geq 0$. Note that the network conditions can be different if we switch l with l' because of the wireless nature of the network. In the example of Figure 2, $a \rightarrow b$ and $c \rightarrow d$ can not transmit simultaneously at the same channel because c is at the interference range of a, and vice versa. Simultaneous transmission would be possible for transmissions $e \rightarrow d$ and $a \rightarrow b$. Note that, if b was at the transmission range of e then $e \rightarrow d$ and $a \rightarrow b$ could not simultaneously transmit using the same channel. For simplicity, the example illustrates the case when $\delta = 0$ but usually the interference range is assumed to be twice the transmission range.

In summary, the interference among concurrent transmissions can dramatically affect the throughput in wireless networks and a careful channel assignment is needed. When using multi-radio technologies in WOBAN, different radio channel assignments will lead to different throughputs flowing from wireless router aggregators to gateways/ONUs. This is due to the fact that different channel assignments result into different sets of active transmission links, called induced graph, and also result into different interferences. Note that an active transmission link between two neighbour nodes exists only if their radio interfaces share a common channel, being able to communicate with each other.

III. Multi-Radio WOBAN Problem Definition

A. General Assumptions

Let us consider the wireless network modeled by a directed graph $G = (V, E)$, where V is the set of nodes, each equipped with one or more interface cards (referred here as radios), and E is the set of feasible transmission links. For simplicity the transmission and interference ranges are considered here to be the same for all radios inside a specific node (the work is easily extended to consider different ranges). We define a matrix I, having E lines and E columns, that summarizes independence among links. That is, $I[l, l'] = 1$ if l can not transmit, on the same channel, simultaneously with l' (not independent).

The subset of routers aggregating local user traffic, and responsible for injecting the user packets into the wireless mesh of the WOBAN, is denoted by $V_A \subset V$. The subset of mesh routers acting as gateways, and attached to an ONU, is denoted by $V_G \subset V$. The set of available channels per radio, that can work simultaneously, is denoted by C. The total number of radios is denoted by R. A global number of radios, and not the number of radios on a per-node basis, allows the allocation of radios to critical regions.

In the following sections we assume precomputed primary routes. A single primary route is assigned to each node for normal traffic delivery. These routes have a gateway router as destination. The nodes can have a different number of radio interfaces but, for simplicity, the set of channels C is the same for all radios. Time-division can be used to allocate traffic transmission from different primary routes. This can happen because nearby communications interfere with each other and the small number of radios does not allow the use of non-interfering channels. The precomputed primary routes are the shortest ones. This is because traffic demands, and the effective transmission rate of radios, oscillate too much. In this fast changing scenario, planning the network routes using another criteria can be too risky. Besides this, unacceptable long routes could be computed. Note that, choosing the shortest routes indirectly leads to a network that is able to support more traffic due to the reduced number of hops and, therefore, reduced use of resources per route. Also, as already stated, gateways and ONUs are usually placed near more traffic intensive areas. Note, however, that the mathematical formulation provided next is general and can be applied to any set of primary routes.

The maximum channel transmission rate is normalized as a unit constant and local traffic demand at nodes is defined proportionally and denoted by D_u, $\forall\, u \in V_A$.

B. Problem Formulation

Let us define P as the set of precomputed primary routes. A specific primary route included in P is denoted by p. Every route $p \in P$ can be defined as a connected serie of links, written as $p: s(p) \in V_A \rightarrow d(p) \in V_G$. We define E^p and $E^{p,u}$ as the set of links used by primary route p and the set of links used by primary route p having node $u \in V$ as its source or destination, respectively.

– <u>Traffic Flow over Channels</u>:

Let $\tau_{c,l}^{p}$ be a binary variable indicating if the traffic of $p \in P$ flows through channel $c \in C$ at link $l \in E^p$. For traffic to flow through channels of primary routes,

$$\sum_{c \in C} \tau_{c,l}^{p} = 1, \forall p \in P, \forall l \in E^p \tag{2}$$

– <u>Limitation on the Number of Radios</u>:

Let ρ_u^c be a binary variable indicating if the node $u \in V$ transmits or receives through channel $c \in C$. Then,

$$\rho_u^c \geq \frac{\sum_{p \in P} \sum_{l \in E^{p,u}} \tau_{c,l}^{p}}{\sum_{p \in P} |E^{p,u}|}, \forall u \in V, \forall c \in C \tag{3}$$

That is, if at least one primary route uses a particular channel at some specific node then a radio becomes necessary and ρ_u^c is forced to be one. The number of radios in use is limited by

$$\sum_{u \in V} \sum_{c \in C} \rho_u^c \leq \mathrm{R} \tag{4}$$

– <u>Channel's Time Division Coefficients</u>:

The transmission bandwidth of a specific channel can be time divided between primary traffic flowing through the channel and primary traffic of links at the interference range that are using the same channel. Note that, although a single route is computed for each node, so that local packets are assigned a specific gateway as destination, a node can be an intermediate for the delivery of traffic originated at some other node. Thus, local and intermediate traffic, at a specific node, can be directed to different gateways. At some interference range links will use the same channel if no extra channels and/or radios are available. Let χ_{MAX} be the load of the most overloaded channel of all links. Then,

$$\sum_{p\in P}\sum_{l'\in E^{p}:I[l,l']=1}\tau_{c,l'}^{p}\times D_{s(p)}\leq\chi_{\mathrm{MAX}},\forall l\in E,\forall c\in C \quad (5)$$

This constraint accounts for all traffic flowing through primary routes at the interference range.

– Objective Function:

The maximization of the network scalability is achieved by the following objective function

$$\text{Minimize } \chi_{\mathrm{MAX}} \quad (6)$$

– Binary and Non-Negative Assignments:

$$\tau_{c,l'}^{p},\rho_{u}^{c}\in\{0,1\};\ \chi_{\mathrm{MAX}}\geq 0 \quad (7)$$

IV. Analysis of Results

In this section we analyze the results obtained, using CPLEX, for the multi-radio WOBAN capacity planning problem. Results were obtained for the SFNet, a WOBAN in San Francisco discussed in [4]. This network has 25 nodes/routers, 5 gateways included.

Simulations were done for 3 and 12 orthogonal channels available. Results in Figure 3 show that the spectrum rapidly becomes exhausted when 3 channels are available and an increase in the number of radios per node rapidly starts to have no effect on the network capacity problem. The lowest value for χ_{MAX} that can be obtained is 2.5. When 12 channels are available the use of multiple radios per node can be much more benefic.

The results in Figure 4 show the average number of hops from radios to the nearest gateway. This average distance tends to decrease as the number of radios in the network increases meaning that the nodes/routers near the gateways are the ones needing extra radios (are more congested). The optimal distribution of radios is obtained when the average distance to gateways stabilizes.

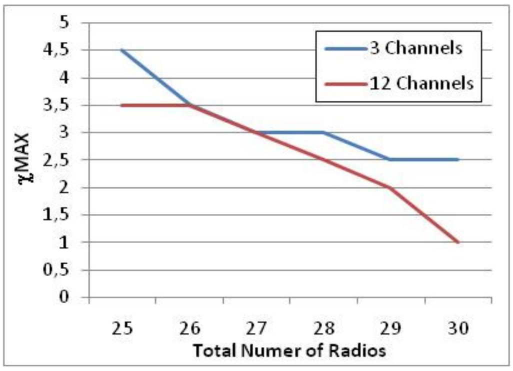

Fig. 3. Load of most overloaded channel.

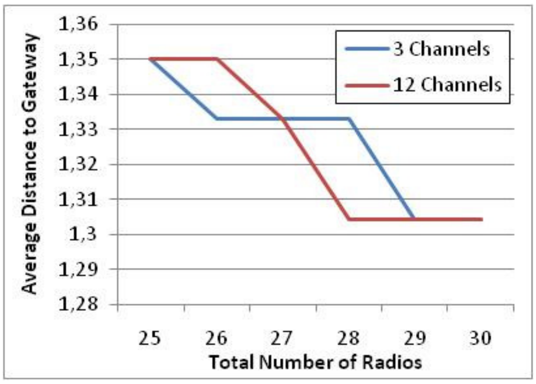

Fig. 4. Average number of hops from radios to nearest gateway.

V. Conclusions

We have analyzed the capacity problem in multi-radio WOBANs. Results show that the use of multiple radios per router is much more effective when 12 orthogonal channels are available while for 3 channels the spectrum rapidly becomes exhausted. The optimal distribution of radios can easily be obtained using the presented approach.

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