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A Radio over Fiber based Wireless Access Network Architecture for Rural Areas

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Abstract— **Recently, "wireless last mile" has received considerable attention since it requires much less infrastructure compared to wireline alternatives such as xDSL and cable modem networks, resulting in a cost-effective solution to the Internet access. However, to date most of the considerations has been focused on densely populated urban areas although broadband service demand in sparsely populated rural areas is continuously increasing. Traffic demand per unit area in such areas is much lower compared to urban areas, but a number of base stations will be required to cover broad areas. In this paper, we propose a radio over fiber based broadband wireless access network architecture for rural areas. It utilizes wavelength division multiplexing for dynamic bandwidth allocation among base stations on demand basis. Characteristics of the architecture, access protocol, and scheduling are discussed. Moreover, a capacity analysis is performed to see the properties of the architecture.**

keywords– wireless access network, radio over fiber, wavelength division multiplexing

I. Introduction

The demand for broadband access has grown steadily as users experience the convenience of high-speed response combined with *"always-on"* connectivity. A broadband wireless access network (BWAN) is a cost-effective alternative to providing users with such broadband services since it requires much less infrastructure compared to wireline access networks such as xDSL and cable modem networks [1]. Thus, these days the so-called *"wireless last mile"* has attracted much attention. However, it has been concerned mainly with densely populated urban areas. Recent survey shows that although penetration of personal computers in rural areas is significant in some countries most of the users still use low-speed dial-up modem for the Internet access [2] [3]. Since in such case broadband services based on wireline networks are prohibitively expensive, wireless access network might be the best solution. In this paper we are concerned with a BWAN for sparsely populated rural and remote areas where a large number of base stations (BSs) are required while traffic demand per BS is much lower compared to densely populated urban areas.

On the other hand, a radio over fiber (ROF) based wireless access network has been proposed as a promising alternative to BWANs due to its cost-effective network architecture [4]. The network comprises a central control station (CS), where all switching, routing, and frequency management functions are performed, and an optical fiber network, which interconnects a number of functionally simple and compact antenna BSs for wireless distribution. The BS has no processing function and its main function is to convert optical signal to wireless signal and vice versa. Due to the simple BS structure, system cost for deploying infrastructure can be dramatically reduced [5]. Moreover, in order to support broadband services millimeter-wave (mm-wave) bands such as 38 or 60 GHz have been considered. In particular, considerable attention has been given to ROF system at mm-wave bands for BWANs to overcome spectral congestion in the lower microwave frequency regions and achieve cost-effectiveness [6]– [9].

In most conventional ROF architectures the CS has a laser diode (LD) and photo detector (PD) pair and a modem for each BS, leading to a complicated CS structure [6] [10]. (In this paper an optical transmitter-receiver pair with a modem is called a transceiver (TRX)). In addition, though wavelength division multiplexing (WDM) is widely employed in ROF systems, its usage is limited to simplifying connection between the CS and BSs [6] [11]. In this paper we propose an ROF architecture for BWANs using WDM for efficient bandwidth allocation. Specifically, the CS has the smaller number of TRXs than the number of BSs, where a TRX consists of optical tunable transmitter (TT) and tunable receiver (TR) pairs and a modem, resulting in simpler CS structure. The CS is interconnected to BSs, each of which is fixed-tuned to one of the available wavelengths, through broadcast-and-select type optical passive device. Although system capacity is limited by the number of TRXs it has simpler CS structure and flexibility in terms of bandwidth allocation. Thus, this system is suitable for BWANs where a number of BSs are required but the average traffic load is small, satisfying the requirements for rural and remote areas.

The paper is organized as follows. Section II describes the proposed network architecture. A medium access protocol (MAC) together with scheduling issue is described in section III. Section IV deals with capacity analysis, which is followed by numerical results in section V. We discuss further study topic, multiplexing techniques for choosing BSs and draw a conclusion in section VI.

II. Network Architecture

A. Architecture Description

The network comprises one CS with K TRXs, N BSs and many fixed subscriber stations (SSs), and each BS is connected to the CS via two optical fibers for uplink and downlink

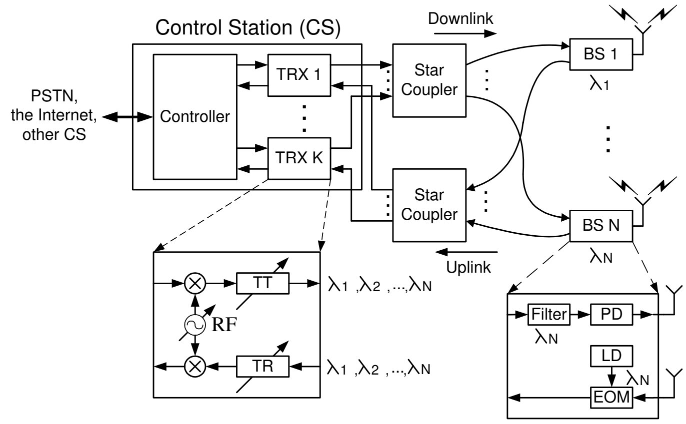

Fig. 1. A proposed radio over fiber access network architecture consisting of K transceivers (TRXs) and N base stations (BSs).

communication, respectively, as shown in Fig. 1. In order to interconnect the CS and BSs optical passive device is used such as optical star coupler or optical combiner/splitter that are insensitive to wavelength. The latter is especially better when the distance between the CS and BSs is large. The BS serves as an access point for an area called *"cell"*. The only function of a BS is to convert optical signal to wireless signal and vice versa. In this paper an ROF architecture is assumed where TDMA/TDD operation is possible. Though there exist several possible options to implement such a system using different technologies (for more information refer to [12]), we present for illustration purposes an example ROF network in Fig. 1. Each TRX in the CS include a modem and a TT-TR pair, tuning range of which covers wavelengths $\lambda_i, 1 \leq i \leq N$. In addition, tuning time is assumed to be negligible, which is a realistic assumption for TRXs with a tuning time of less than tens of nanoseconds [13]. The modem in each TRX has the capability to change RF channels. On the other hand, BS i is fixed-tuned to the wavelengths $\lambda_i, 1 \leq i \leq N$ that could be accomplished using an optical filter. One wavelength is used as a carrier for downlink and uplink data transmission. As a result, the network is of broadcast-and-select type where any TRX at the CS can access any BS by tuning optical wavelength unless wavelength collision occurs. In this architecture we assume $K < N$.

Note that the architecture has a possibility that if multiple BSs are tuned to the same wavelength the total number of BSs could far exceed the number of wavelengths. In this case, the areas covered by the BSs tuned to the same wavelength are considered as a single cell. For proper operation, they should be spaced apart so that there is no co-channel interference between them, and propagation delay over optical fiber between the CS and the BSs has to be identical. Using this approach a broader area can be covered with small number of wavelengths. From now on, however, we consider only the case when the number of BSs equals the number of wavelengths.

B. Basic Operations

The system operates in TDMA/TDD mode. In order for a TRX to support a BS it must know the wavelength and the RF channel used by the BS. Regarding RF channel we assume that RF channels are predetermined and fixed for each BS based on frequency reuse technique. The CS maintains a table listing BS identification (ID) number, its wavelength and RF channel.

For downlink transmission from CS to BS i user data first modulates RF source which, in turn, modulates optical light source that is tuned to λ_i. This signal is carried over the downlink optical fiber to the BS i, where the optical signal is converted into wireless signal and emitted from the BS. For uplink transmission, the wireless signal received by BS i is changed into optical signal by modulating light source which is fixed-tuned to λ_i. It is then transported over uplink optical fiber to a TRX, where its TR tuned to λ_i first demodulates optical signal to obtain electrical signal which is again demodulated in the RF domain to acquire user data.

The time period during which TT (TR) stays tuned to a certain wavelength corresponds to the bandwidth allocated for downlink (uplink) communication for the BS, suggesting flexible bandwidth management is possible. Note that more than one TRX is not allowed to support the same BS at the same time due to wavelength collision. So, the maximum bandwidth that can be allocated to a BS is confined to the TRX capacity while the system capacity is K times the TRX capacity. Notice that it is easy to extend system capacity by adding more TRXs to the CS. Considering modern dense WDM technology hundreds of BSs can be supported by a CS. In addition, recent progress in ROF systems at mm-wave bands suggests a TRX capacity could amount to a few hundreds Mbps. Therefore, in most cases K TRXs that is much smaller than N will be sufficient to service sparsely populated areas if user bandwidth is limited to a few Mbps. In summary, the architecture has two salient features: (1) efficient and flexible bandwidth allocation and (2) simple extension of system capacity.

III. Medium Access Protocol

Since propagation delay between the CS and BSs in the ROF networks under consideration could be large compared to packet transmission time, CSMA-like MAC protocol is not appropriate. As a result, the proposed architecture assumes a centralized MAC entity located at the CS offering a reservation-based, collision-free medium access.

A. Frame Structure

For each TRX a fixed-size super-frame is defined, which determines the "air-time" given to each BS (defined as a frame), i.e., the time period each BS uniquely uses to communicate with SSs located in its cell (Fig. 2). The super-frame provides users with data slots, each of which fits a minimum data packet. Even though the length of the super-frame is fixed to t_{SF} seconds, the duration of the frame assigned to each BS (t_{F_j} with respect to $BS\ j$) may be variable as long as

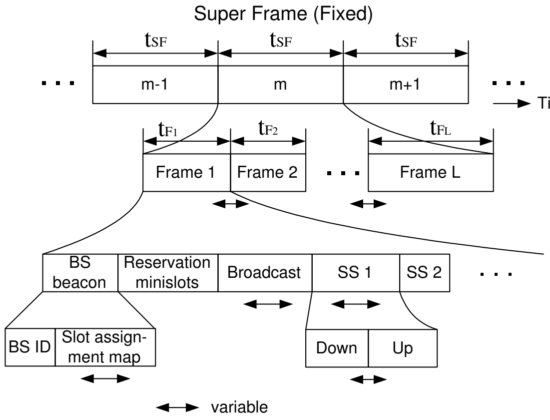

Fig. 2. Frame structure. For simplicity, guard time is not shown.

$$\sum_{i=1}^{L} t_{F_j} \leq t_{SF}$$

where L denotes the number of BSs supported by a TRX. Note that depending on traffic demands from BSs each TRX could have different L values.

Each frame belonging to a certain BS begins with *"beacon"* field that consists of BS ID and *"slot assignment map"* specifying the start slot position and length for each SS. The following field is *"reservation minislots"* which is accessed by SSs in a contention-based way that have not yet reserved any slots but have data to transmit. It is up to the CS to decide on the number of the minislots for each BS. An uplink reservation minislot contains the SS ID and quality of service (QoS) parameters for the traffic. For contention resolution conventional method such as p-persistence can be utilized. The results of reservation trial in the previous super-frame is broadcast in the *"broadcast"* field, which is followed by downlink and uplink slots assigned to each SSs as specified in the slot assignment map. A minislot is attached to each uplink slot from an SS. Using this minislot the SS can request more bandwidth if necessary, which makes it unnecessary for the SS to send a request in a contention-based way.

Note that since the CS has K TRXs, up to K super-frames can be supported simultaneously. In order for a TRX to access a BS it must have appropriate information; that is, the wavelength of the BS, tuning instant for TT and TR, and RF channel of the BS. A scheduler at the CS provides the information and controls each TRX. We assume that super-frame time is larger than sum of maximum round-trip delay and processing time for scheduling and reservation request.

B. Scheduling

Since scheduling issue in broadband wireless networks is beyond the scope of the paper, we confine our discussion to requirements of scheduling algorithm for the proposed architecture and consider only a simple case where each TRX has a fixed-size capacity of C data slots and connection-oriented traffic requesting constant bandwidth during its lifetime. That

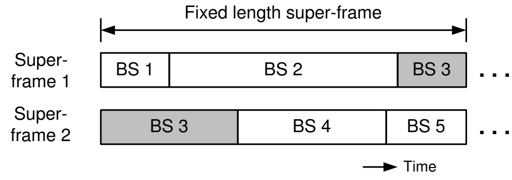

Fig. 3. Packing of five frames into two super-frames where frame three is fragmented in such a way that no wavelength collision occurs.

is necessary to justify capacity analysis in the next section. The main task of a scheduler is to allocate frames to TRXs such that it should be efficient in bandwidth usage and avoid wavelength collision. The output of it provides each TRX with wavelengths to which it has to tune, tuning instant and duration for each of them, and the corresponding RF channels for BSs. It also prepares downlink data blocks for each BS and associates them with the corresponding TRX every frame time. As BWANs considered in this study might have hundreds of BSs connected with one CS, scheduling algorithm should be fast and simple.

The scheduling problem can be translated into how to pack N frames for N BSs into K super-frames. If fragmentation of a frame is allowed (i.e., multiple TRXs support a BS in distinct time periods within a super-frame time) bandwidth usage will be more efficient although it requires overhead. Fig. 3 shows an example indicating how to pack five frames into two super-frames where frame three is fragmented. The algorithm must keep fragmented frames from causing wavelength collision.

For a new request requiring B_{new} (in units of data slots) in every super-frame in BS i two conditions are checked out for admission control

$$\begin{aligned} &(i) \quad B_U^i + B_{new} \leq C \\ &(ii) \quad \sum_{j=1}^{N} B_U^j + B_{new} \leq K \cdot C \end{aligned} \tag{1}$$

where B_U^j is the bandwidth being used in BS j. The first line is required to avoid wavelength collision, while the second line says total traffic load must be less than or equal to the CS capacity.

IV. Capacity Analysis

In this section, assuming overhead associated with fragmentation in scheduling is negligible a capacity analysis of the system based on multitraffic loss system is performed [14] [15]. With the assumption that call arrival processes are Poisson, the original version of multitraffic loss system provides state distribution in steady state in a closed-form equation. It is so general that it holds for arbitrary resource sharing policies [14].

The basic idea behind our analysis comes from the fact that traffic intensity from BS i can be modeled as a Poisson process if traffic from an SS is a Poisson process because a sum of Poisson processes is also a Poisson process. So, we don't consider individual traffic from a SS; instead, aggregate traffic load to a BS is taken into account. In addition, traffic from BS i can be considered as belonging to class i traffic. Here, the constraints on wavelength collision and system capacity of Eq. (1) are integrated into resource sharing policy as described later. We make the following assumptions for the analysis.

A1) A connection arrival to BS i is a Poisson process with the mean arrival rate being a_i, and the bandwidth demand of it is one slot.
A2) A connection of BS i has a connection life time with mean $1/\mu_i$.
A3) A connection which cannot be accepted by the system is blocked and cleared.

Let $A_i = a_i/\mu_i$ be the traffic intensity from BS i. Under these assumptions, we consider the state description $\mathbf{n} = (n_1, \ldots, n_N)$ where n_i is the number of connections of BS i connected. The set of allowable set $\mathbf{\Omega}$ of $\mathbf{n}$ is determined by the number of transceivers K, transceiver's capacity C and wavelength collision constraint. Any $\mathbf{n}$ of the allowable set should satisfy:

$$\mathbf{n} \in \mathbf{\Omega} \quad \Rightarrow \quad 0 \leq n_i \leq C, \quad i = 1, \ldots, N \tag{2}$$

$$\sum_{i=1}^{N} n_i \leq K \cdot C \tag{3}$$

Eq. (2) is necessary to avoid wavelength collision, while Eq. (3) says bandwidth demands cannot exceed system capacity. In other words, the two equations correspond to the first and the second line of Eq. (1), respectively. For any resource sharing policy, a product form solution prevails in steady state; that is, the probability that the system is in $\mathbf{n}$ in steady state is given by [14]

$$\mathbf{P}(\mathbf{n}) = G^{-1}(\mathbf{\Omega}) \prod_{i=1}^{N} \frac{A_i^{n_i}}{n_i!} \quad \text{for} \quad \mathbf{n} \in \mathbf{\Omega} \tag{4}$$

where

$$G(\mathbf{\Omega}) = \sum_{\mathbf{n} \in \mathbf{\Omega}} \left(\prod_{i=1}^{N} \frac{A_i^{n_i}}{n_i!} \right) \tag{5}$$

Suppose a test BS i, then the blocking probability of a connection that requests a bandwidth through the BS is given by

$$\mathbf{P_b} = \sum_{\mathbf{n} \in \mathbf{\Omega_i^+}} \mathbf{P}(\mathbf{n}) \tag{6}$$

where

$$\mathbf{\Omega_i^+} = \{\mathbf{n} \in \mathbf{\Omega} | n_i = C \text{ or } \sum_{k=1}^{N} n_k = K \cdot C\} \tag{7}$$

That is, the connection request is blocked either when (1) the bandwidth used at the BS is C or (2) the total bandwidth of all connections is system capacity $K \cdot C$. Given $\mathbf{P}(\mathbf{n})$ bandwidth utilization is simply calculated by

$$\mathbf{U} = \sum_{\mathbf{n} \in \mathbf{\Omega}} |\mathbf{n}| \cdot \mathbf{P}(\mathbf{n}) \tag{8}$$

V. Numerical Results

One problem with Eq. (4) in calculating $\mathbf{P}(\mathbf{n})$ is that computational burden greatly increases as C or N grows, so we consider only the cases where C and N are computationally tractable for analysis. Fig. 4 indicates blocking probabilities versus traffic load to the system with different K values when N is 10 and C is 20. With $K = 1$ Eq. (4) reduces to the Erlang-B formula for $M/M/m/m$ queueing system. In such case blocking probability is simply given by $\mathbf{P_b} = \sum_{|\mathbf{n}|=C} \mathbf{P}(\mathbf{n})$. In case when K is more than one an interesting point is observed. Blocking probabilities are not different regardless of K up to some traffic load. After that point (called a *"critical point"*) a distinguishable difference is observed. For example, the blocking probabilities for $K = 3, 4$ are the same up to a traffic intensity of 18 Erlangs. However, after that point the difference becomes large as traffic increases.

To explain it more clearly, refer to Fig. 5 that indicates blocking probabilities versus traffic load when $K = 3, C = 20$ and $N = 10$ (solid line) together with cases when $K = 1$, $C = 60$ (dotted line) and $K = 5$, $C = 20$ (dashed line). When the traffic load is smaller than the critical point connection blocking is governed mainly by Eq. (2) (i.e., wavelength collision constraint) because the probability that total bandwidth demand is greater than the CS capacity is very small. That is, when $K > 1$, connection blocking is constrained by wavelength collision regardless of K until traffic load reaches the critical point. On the other hand, as traffic load grows Eq. (3) plays a dominant role in determining connection blocking. In this case the system behaves as if it had a single server with the same capacity as the CS in terms of blocking probabilities. That is, after the critical point blocking probabilities follow those of single server with the same total aggregate capacity (see the dotted line for $K = 1, C = 60$).

The figure also shows that given K TRXs the critical point can be determined as a cross point between the line of blocking probabilities for a single server with the same total capacity (i.e., $K = 1, C = 60$) and that for a larger number of TRXs (e.g., $K = 5, C = 20$). Using discrete-event simulation blocking probabilities of Eq. (6) can be easily calculated, however, critical points cannot be simply observed since they take place at very low values. In Fig. 4 simulation results are depicted as small circles. It implies the analytical model developed in the last section can be utilized to get an insight into how the number of TRXs impacts on system performance.

VI. Discussion and Conclusion

Although we assume in this paper frequency bands for each BS are predetermined, if it could be dynamically changed by the CS the proposed architecture leads to an interesting problem. Essentially, it then has two-degree of freedom in the time and frequency domain, respectively. In such case, at any given time the CS changes time periods and frequency bands

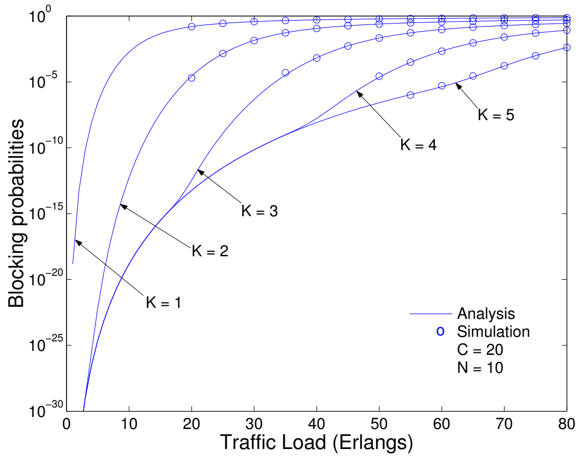

Fig. 4. Blocking probabilities when $N = 10$ and $C = 20$.

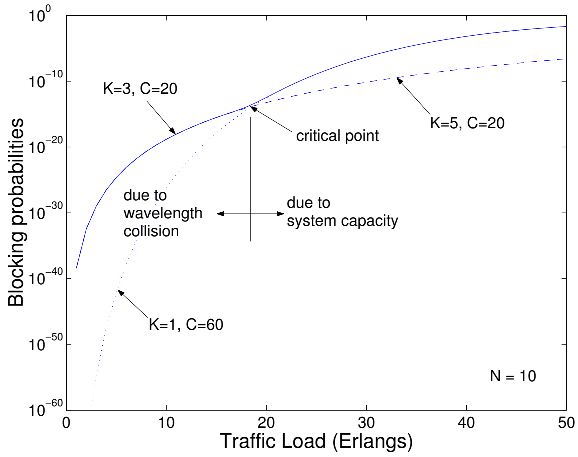

Fig. 5. Blocking probabilities when $K = 3$, $N = 10$ and $C = 20$.

for each cell, where not only bandwidth allocation but also interference among cells can be taken into account for better system performance. Since adjacent cells must not utilize the same frequency band at the same time, it is closely related to graph coloring problem that is an interesting topic for our future study.

In our architecture we exploit only optical wavelength for choosing BS, however, when the number of BSs to be independently selected is larger than the number of available wavelengths we could rely on an extra degree of freedom (in addition to the wavelength) at the cost of increased hardware complexity. That is, another multiplexing techniques (e.g., time, space, signal polarization, codes, subcarriers) can be utilized over WDM. For instance, a popular electrical multiplexing scheme is subcarrier multiplexing, whereby multiple electrical signals are multiplexed in the RF domain and then modulate a single optical source. Though the necessary enabling technologies have yet to mature, they provide a way to increase the number of BSs that should be independently accessed by the CS while achieving simple network configuration, which has been discussed in [16].

In conclusion, in this paper, a radio over fiber based broadband wireless access network architecture has been proposed for sparsely populated rural and remote areas. In the architecture a control station has optical tunable-transmitter (TT) and tunable-receiver (TR) pairs and utilizes wavelength division multiplexing to access numerous antenna base stations, each of which is fixed-tuned to a wavelength, for efficient and flexible bandwidth allocation. Although its capacity is limited by the number of TT/TR pairs, it has simpler CS structure while maintaining trunking efficiency. Characteristics of the architecture, access protocol, and scheduling have been discussed, and capacity analysis based on multitraffic loss system was performed to show some properties of the proposed architecture.

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