Challenge: CeTV and Ca-Fi – Cellular and Wi-Fi over CATV

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ABSTRACT

This paper introduces a novel concept that enables transmitting wireless communication over CATV networks. We present the architecture of a system for Cellular Communication over CATV (CeTV) and review the required modifications to the cable network. These modifications affect only the cable network, thereby enabling the system to operate with unmodified cellular phones. In addition to improving in-building coverage, the CeTV system significantly increases the capacity of the cellular network. We also present the architecture of a Wi-Fi (IEEE 802.11) over CATV (Ca-Fi) system. The implementation of the Ca-Fi system requires improving the MAC protocol used by the Access Points that are deployed within the cable network. However, it does not require modifying the users' devices. We present a few alternative MAC protocols which aim at polling 802.11 stations using the Distributed Coordination Function (DCF). These protocols deal with, and take advantage of the special characteristics of the CATV network. The performance of the proposed protocols is evaluated analytically and via simulation.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design – *Wireless communication*;
C.4 [**Performance of Systems**]: – *Design studies, Reliability, availability, and serviceability*

General Terms

Design, Performance.

Keywords

Wireless LANs, Cellular networks, CATV, IEEE 802.11, MAC, Polling.

1. INTRODUCTION

This paper presents a novel concept of *Cellular Communication* over *Community Antenna Television (CATV)*. This concept is implemented by *radio relaying* of *cellular* signals to-and-from the users' premises through the cable network. The CATV network actually operates as a distributed antenna with cellular Base Stations at each of the CATV *Head Ends*. The poor long aerial channels are replaced by the combination of long cables with excellent propagation characteristics and very short aerial channels.

We refer to the system which is based on this proposed concept as *Cellular over CATV* (CeTV) [11],[13]. The implementation of CeTV requires connecting small low cost units to the cable outlets, and a few modifications to the physical layer of the CATV network. It does not impose any modifications on the users' cellular phones. The implementation will solve indoor coverage problems and will enable a very high quality in-building cellular service. In addition, since outdoor cells will not have to deal with most of the indoor traffic, larger cells can be deployed and the number of outdoor cells can be drastically reduced.

Following the concept of CeTV, we present a new architecture that enables the transmission of Wi-Fi over CATV (Ca-Fi) [14],[15]. In the proposed system, Wi-Fi signals (following any of the standards: IEEE 802.11a/b/g/e/n) are transmitted from the customers' premises over the CATV infrastructure to an *Access Point*, which is located at the CATV *Fiber Node*. The possible applications of Ca-Fi include the provision of wireless access to home users as well as easy deployment of IEEE 802.11 networks in office buildings and hotels (which usually already have CATV wiring).

We emphasize that the concept presented in this paper considerably differs from other solutions that enable the transmission of data or voice in CATV networks. The solutions for transmitting voice are mainly based on the Data-Over-Cable Service Interface Specification (DOCSIS) [4] (i.e. require a cable modem) and on Voice over IP techniques. On the other hand, CeTV relays *radio signals*, thereby requiring only a low cost device at the cable outlet and allowing using unmodified cellular phones. Using Wi-Fi in conjunction with a cable modem requires also an access point, whereas in the proposed solution there is no need for a cable modem or for an access point.

Transmitting Wi-Fi signals over the CATV infrastructure enables the establishment of a *centralized managed* wireless Wide Area Network (WAN). The ability to provide a centralized Wi-Fi service has some major advantages. First, the centralized service will reduce the subscribers' need to purchase and maintain personal devices. Second, it will enable provision of future wireless access technologies without a need to upgrade or replace the customers' equipment. Finally, the customers will enjoy a higher level of service and security than the level most of them will experience with a privately managed wireless network.

We present the proposed architectures and briefly review the modifications to the physical layer of the CATV network. Then, we show that carrying Wi-Fi signals over the CATV infrastructure introduces some new obstacles which are not accounted for by the legacy IEEE 802.11 standards (for a detailed description of IEEE

MobiCom'05, August 28–September 2, 2005, Cologne, Germany.

802.11 see [6]). We propose a few possible alterations to the MAC protocol used by the access point that can be utilized in order to overcome these obstacles. We point out that these MAC modifications affect only the access points deployed by the CATV operator and *do not require any changes* to the users' devices.

It seems that the IEEE 802.11 Contention Free Mode (Point Coordination Function - PCF) is the most desirable mode of operation in a Ca-Fi network. However, the implementation of this mode is not mandatory, and therefore, in practice it is not implemented in most of the 802.11 devices. We propose to use this mode in order to communicate only with stations supporting it. The Distributed Coordination Function (DCF), which is based on the CSMA/CA mechanism, is very inefficient in a network with long propagation delays and in which all nodes are hidden from each other. Thus, we propose to use this mode *only* for associating and authenticating new stations.

We propose three new protocols which take advantage of *switching and sensing* capabilities incorporated at the Ca-Fi physical layer. These protocols require the 802.11 stations to operate in the distributed (DCF) mandatory mode. The first protocol is a *Virtual Polling Protocol* which uses standard 802.11 control messages to silence some of the nodes and to poll other nodes. We then propose an *enhancement* to the Virtual Polling Protocol that efficiently utilizes idle time. Finally, we present a *Reservation Protocol* that senses which stations have data to transmit and polls only these stations.

The performance of the proposed protocols is evaluated analytically and via simulation. Since there is a vast amount of research regarding the DCF and PCF modes (e.g. [1],[9], and references therein), we focus on performance evaluation of the new protocols. We first provide an approximate analysis of the Virtual Polling Protocol. Since the performance of the other protocols does not seem to be analytically tractable, we have developed a simulation model of the Ca-Fi system. We show that the simulation results are *very close* to the analytic results. Then, we present simulation results regarding the proposed enhancement to the Virtual Polling Protocol and regarding the Reservation Protocol.

Obviously, the issues of Cellular and Wi-Fi over CATV have not been thoroughly studied. Yet, numerous papers study MAC enhancements for IEEE 802.11. For example, the applicability of IEEE 802.11 standards for outdoor networks with a high propagation delay has been considered in [7]. In addition, [10] proposes a new DCF based polling scheme which does not require to modify the stations. Finally, in the considered network all nodes are hidden. A similar setting can take place in IEEE 802.11 networks with directional antennas (see for example, [3] and references therein).

This paper is organized as follows. Section 2 presents the concept of wireless over CATV and describes the physical layer aspects. In Section 3, we describe a few alternatives for the MAC layer design. In Section 4, we evaluate the performance of the proposed MAC protocols. Section 5 summarizes the main results and discusses open problems.

2. PHYSICAL LAYER

2.1 The CATV Infrastructure

Modern CATV networks are implemented according to the Hybrid Fiber Cable (HFC) architecture. Accordingly, fibers are arranged at a star topology and carry the signals from the CATV center (Head End - HE) to the fiber nodes. At each fiber node the signals are launched into the coaxial cables. The cables are arranged in a tree topology and carry the signals from the node to the indoor subscribers. Each node serves 1,500 to 2,000 customers. The network coverage at a service area is usually almost complete (both indoor and outdoor).

The CATV infrastructure carries multi channel modulated radio signals. The radio signals in all channels are guaranteed almost constant signal levels and signal to noise ratio, at all the residential outlets.

The HFC network architecture can support bi-directional communication and signaling between the subscriber unit and the HE. Bi-directional communication is achieved by deploying amplifiers that work in both directions. CATV networks operate at the frequency range of 5-860 MHz. However, the frequency limit of most of the network elements (fibers, cables, and combiners/splitters) is higher than 1.2GHz, where the linear amplifiers along the network induce the 860MHz upper limit.

2.2 Cellular over CATV (CeTV)

The concept of Cellular Communication over Community Antenna Television (CATV) is implemented by radio relaying of the cellular signals to and from the subscribers' premises through the cable network. The cable network actually operates as a distributed antenna with matching elements at the CATV outlets and Base Stations of the cellular operators deployed at the CATV Head Ends.

The operation of the *CeTV* system is illustrated in Figure 1. A device located at the cable outlet acts as the interface between the cables and the air. It separates the cellular downlink signals from the CATV signals, converts them into the original cellular frequencies and transmits them to the air. Similarly, it receives uplink signals from the air and transmits them on the CATV network to the Base Station. Each device can transmit up to 1mW of signal power to serve an indoor area of 100-150 sq. meters. We shall refer to this device as *RU (Residential Unit)*.

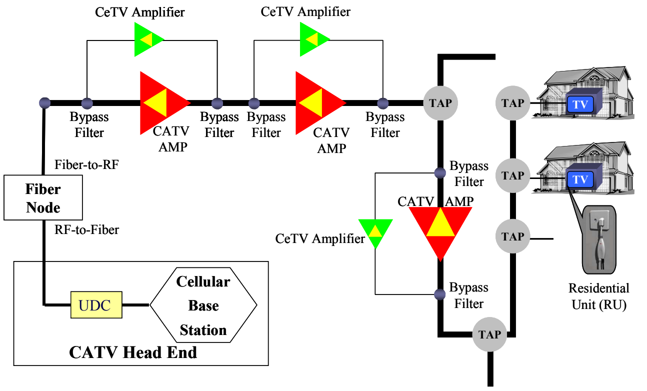

Figure 1: The CeTV system architecture.

At the fiber node a radio-to-fiber conversion takes place (as done for all CATV signals). Finally, at the Head End, an *Up-Down Converter (UDC)* separates the cellular uplink signals from the CATV signals, converts them into original cellular frequencies and transmits them to the Base Station. Similarly, it receives downlink signals from the Base Station and transmits them on the CATV network to the RUs. We note that cellular uplink and downlink signals are transmitted on different bands (i.e. according to Frequency Division Duplex - FDD), and therefore, they are transmitted on different bands over the CATV infrastructure.

In order to enable the transmission of the cellular signals, the frequency range of the coax network is expanded to 1200MHz. To that end, the network's amplifiers are modified by the addition of bi-directional by-pass linear amplifiers operating in the frequency range of 900 to 1200MHz. The modification enables bi-directional free linear flow of the frequency converted cellular radio signals through the CATV network. Due to the fact that CATV networks operate at the frequency range of up to 860MHz, the deployment of CeTV does not affect the CATV network performance.

2.3 Wi-Fi over CATV (Ca-Fi)

A similar solution (*Ca-Fi*) can be applied in order to *radio relay* Wi-Fi signals from 802.11 stations through the RUs at the subscribers' premises to Wi-Fi access points located at the CATV Fiber Nodes. The Ca-Fi system is implemented by allocating a portion of the newly generated bandwidth to carry Wi-Fi signals. Since the system must work with legacy Network Interface Cards and due to the particularities of the Wi-Fi (IEEE 802.11) MAC, there is a need for MAC enhancements at the access points deployed by the CATV operator (see Section 3). We note that additional elements, which are required for the operation of the physical layer, support these MAC enhancements.

The IEEE 802.11 access points are deployed in the Fiber Nodes, since the 802.11 ACKTimeout, defined by the different vendors, usually does not allow a propagation delay corresponding to more than 2.5km[1]. The distance between the Fiber Node and the subscriber's premise is usually less than 2km.

CeTV can be quite easily implemented, since both the cellular and CATV systems are FDD systems. Namely, in both systems uplink and downlink signals are transmitted over separate frequency bands. Conversely, Wi-Fi is a Time Division Duplex (TDD) system, in which uplink and downlink signals are transmitted over the same frequency band. However, TDD access may cause oscillations at the active elements of the network, particularly at the frequency converters (i.e. the UDCs and the RUs) and the by-pass amplifiers.

Thus, in order to prevent oscillations, there is a need to separate the uplink and downlink signals at any active element of the network. This is done by a switching mechanism at the RUs that enables the RUs to block transmissions in the uplink or the downlink. The switching mechanism can be controlled either by an activity detector at the RU or by a central management system using a dedicated control channel. Furthermore, a TDD to FDD conversion is employed both at the RUs as well as at the UDC. Namely, uplink and downlink signal are transmitted in different frequencies.

An additional benefit of the switches is the elimination of accumulated noise at the uplink, which could limit the number of users. Furthermore, the centrally controlled switching system enables the transmission of Wi-Fi frames from the access point to a specific station or to a specific group of stations.

3. WI-FI OVER CATV – MAC LAYER

An immediate outcome of carrying the Wi-Fi signals from the Fiber Node to the customers' premises is an increase in the propagation delay. The transmission range in the WAN topology is up to 2km which results in propagation delay of up to 10μsec[2]. Such a propagation delay significantly decreases the throughput of CSMA/CA systems due to an increased number of collisions.

In addition, the CATV tree topology carries signals only downlink and uplink. Signals from one branch to another are isolated. Thus, in practice, all stations are hidden. IEEE 802.11 resolves the hidden node problem through the RTS/CTS (Request to Send/Clear to Send) handshake. However, this mechanism is inefficient when the number of hidden stations is large. Thus, it is clear that the DCF (CSMA/CA) protocol with the RTS/CTS handshake is inadequate for the CATV WAN topology.

Due to these obstacles, it seems that in Ca-Fi, the polling based access mechanism (PCF) outperforms the CSMA/CA (DCF) protocol. However, as mentioned above, in practice, most 802.11 stations do not support the PCF mode. Thus, we propose novel Virtual Polling and Reservation access control methods that utilize the PHY switching system (described in Section 2.3) and that are compatible with stations operating in the DCF mode. Although the medium is governed by the standard DCF mode, the proposed protocols provide transmission guarantees with contention free frame transfer. The access point will alternate between a Contention Free Period (for stations supporting the PCF mode), a period in which one of the new polling and reservation mechanisms will be used, and a Contention Period (legacy DCF which will be used for authentication and association).

3.1 Virtual Polling Protocol (VPP)

We propose a *Virtual Polling Protocol* (VPP) which requires modifications to the access point MAC protocol and which operates with stations using the DCF mode. This protocol utilizes the PHY switching system to poll a specific station by selectively transmitting CTS messages to all other stations.

According to the standard DCF mode, each station maintains a Contention Window (CW) that is used to determine the time (in slots) it has to wait before transmission. A station wishing to transmit selects a backoff time uniformly distributed in the interval (0 , CW-1). Once a station detects that the medium is free, it begins to decrement its backoff counter. The backoff counter only begins to decrease after the medium has been free for a Distributed Interframe Space (DIFS) period. In the VPP, the access point gains control of the medium by waiting a shorter time between transmissions than the stations. Namely, the access point waits a Short Interframe Space (SIFS) period between transmissions instead of the standard DIFS + BackoffTime. The access point polls the stations in a round robin manner using the method described below. Then, it sends to the stations all the messages accumulated in its downlink queue.

Figure 2 illustrates the operation of the protocol. In order to poll a station, say the n^{th} station, the access point communicates (via the control channel) with the switch at the RU of the n^{th} station, and blocks the downlink transmission to this station. Then, it sends a CTS message destined to the n^{th} station with a duration field set to the size of the contention window. Upon receiving this CTS message all stations update their Network Allocation Vectors (NAVs) and refrain from accessing the medium for the duration reported by the CTS message. The n^{th} station, which does not receive a CTS, senses the medium as idle and embarks with the backoff procedure. If it has impending frames, a single frame[3] is sent whenever the backoff counter reaches zero (i.e. before the end of the contention

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[1] The ACKTimeout is not explicitly defined in the specifications. Therefore, we have performed extensive experiments with numerous 802.11 devices in order to evaluate their ACKTimeout values. We have found that as long as the distance between the access point and the station is less than 2.5km, the proposed system will function properly (for more details see [2]).

[2] IEEE 802.11 has been designed aiming at distances of less than 200m, associated with a propagation delay of less than 1μsec.

[3] We note that if the RTS/CTS handshake is invoked, RTS will be sent, a CTS will be received, and then the data frame will be sent.

window). If the n^{th} station has no waiting frames, the access point polls the next station, after it has waited for CW + DIFS + MaxPropagationDelay.

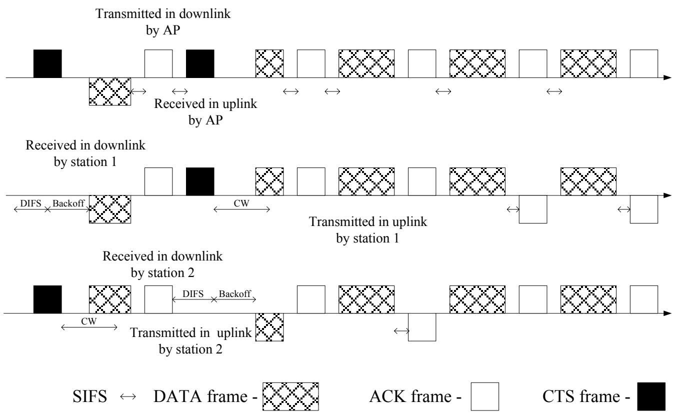

Figure 2: An example of the operation of the Virtual Polling Protocol in a network with an access point and 2 stations.

In case the n^{th} station transmits a frame, the transmission can terminate well after the end of the contention window. Therefore, there is a need to update the NAVs of the other stations. In order to do it, the access point *broadcasts* (in the downlinks towards these stations) every bit received in the uplink of the n^{th} station. The broadcast is done at the physical layer, disregarding the frame's content. Accordingly, all stations update their NAVs and refrain from accessing the medium. Finally, the access point sends an ACK in all the downlinks. This ACK again causes an update to all the NAVs.

We note that since inherently, there should be no collisions, the contention window value is always equal to its minimum value[4]. In our analysis we shall denote the value of the minimum contention window by $CW_{\min}$.[5]

3.2 Talk-Back enhancement of the VPP (VPP-TB)

According to the IEEE 802.11 specifications, when stations update their NAVs, they can only *increase* the time in which they should refrain from accessing the medium. Thus, if a station transmits a frame that is significantly shorter than the contention window, the other stations will not update their NAVs and the medium will be idle for a while. Thus, the access point can use this idle time in order to transmit a frame in the downlink to one of the stations. We refer to this enhancement as the *Talk-Back enhancement of the VPP (in short VPP-TB)*.

Unlike in the VPP, the access point does not send the frames in an exhaustive manner. Alternatively, after every uplink frame, the access point sends a frame in the downlink according to First-In-First-Out (FIFO) order. As will be shown is Section 4, the proposed enhancement not only improves the operation of the protocol but is also essential in the Reservation Protocol described below.

3.3 Reservation Protocol (RP)

In the Reservation Protocol (RP) the stations transmit a single frame in a round robin manner and the access point replies to each uplink frame with a frame in the downlink (similarly to the VPP-TB). The advantage of this protocol is that during every cycle *only stations that have pending frames transmit*.

At the beginning of a cycle, the access point stops transmitting for a DIFS + CW + MaxPropagationDelay interval. The stations sense that the medium is idle and embark the backoff procedure. Stations that have waiting frames try to transmit during the contention window (we refer to it as the *reservation phase*). These transmissions will probably collide at the access point. Thus, the access point will not respond with ACKs and the stations will realize that their frames have been lost.

The RUs are capable of channel assessment, i.e. they can detect activity. Thus, RUs that sense activity during the *reservation phase* will update the access point via the control channel. Accordingly, the access point will determine which stations have pending frames. The access point will poll these stations using the VPP. Namely, it will send CTS messages only regarding stations which tried to transmit.

We note that since the frames collide during the *reservation phase*, all the stations that try to transmit during that phase will double their contention window. The contention window will be reduced to its minimal value ($CW_{\min}$) after a successful transmission. Thus, in the Reservation Protocol the VPP should be operated with a contention window which is equal to $2CW_{\min}$. Since this implies a higher chance of idle times after the uplink transmission, the VPP-TB version is used.

3.4 Contention Free Period

The Contention Free Period (CFP) is based on the IEEE 802.11 polling scheme controlled by the Point Coordinator (PC) operating at the access point. During the CFP the access point polls the CF-Pollable stations according to the 802.11 PCF frame transfer procedure. Although some stations are not CF-Pollable, all these stations must be able to receive the frames, signaling the beginning and the end of the CFP, and to refrain from transmitting during the CFP.

We note that in [7] it is mentioned that the PCF protocol seems to be infeasible in networks with high propagation delays. Yet, we argue that a minor manipulation in the PCF protocol, which is operated at the access point, can make it feasible. According to the PCF protocol, if a CF-Pollable station does not respond to a CF-Poll within the Priority Interframe Space (PIFS) period, following a transmission from the access point, then the access point shall resume control and may transmit its next frame. However, a high propagation delay may lead the access point to mistakenly assume that the polled station did not respond within the PIFS period. This difficulty can be easily resolved if the access point waits for a period of MaxPropagationDelay + PIFS before resuming control and transmitting its next frame. MaxPropagationDelay shall be determined according to the maximum radius of the CATV network.

3.5 Contention Period

To allow new stations to perform authentication and association, some of the channel time is dedicated to Contention Period. During this period the stations operate according to the DCF protocol (CSMA/CA). Since all the nodes are hidden from each other, we partially solve the hidden node problem by *broadcasting* every bit received in the uplink to all the stations except the transmitting sta-

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[4] Although there are no collisions, there is a low probability that packets may be lost in the radio channel between a station and a RU. In our current analysis, we ignore such a scenario.

[5] The backoff time is uniformly distributed in the interval (0, CW - 1). Therefore, for simplicity of the presentation, $CW_{\min}$ is actually defined here as min(CW) - 1.

tion. As in the VPP, the broadcast is done disregarding the frame's content.

4. PERFORMANCE EVALUATION

4.1 Virtual Polling Protocol (VPP)

In this section we provide an analytical model of the Virtual Polling Protocol and derive approximate results under the assumption of a Poisson arrival process. In the next section we shall present simulation results regarding VPP and show that the analytic and the simulation results are very close. We note that in this section and in the following section we assume that the RTS/CTS handshake is disabled.

For simplicity of the *presentation*, we assume that all stations are identical[6]. The frame arrival process to each uplink queue (at a station) is Poisson with intensity λ_u. The frame arrival process to the *single* downlink queue (at the access point) is Poisson with intensity λ_d.

The transmission time of a given data frame is defined as the transmission duration of the *data frame* itself (including the MAC header and the PHY overhead), the maximum propagation delay, the duration of a SIFS, the transmission duration of the following ACK (including the PHY overhead) and the maximum ACK propagation delay. Namely, the transmission time is defined as the time from the beginning of the frame transmission until the end of ACK reception, assuming that the propagation delay is maximal. For brevity, we shall denote MaxPropogationDelay by τ.

The lengths of the SIFS, the ACK, and τ are constants. Therefore, for a given transmission rate, the transmission duration is a linear function of the number of bytes in a frame. Thus, we denote the group of possible transmission times by M ($|M|$ is bounded by the Maximum Transmission Unit). The transmission time (in seconds) is denoted by t_i $(i \in M)$. The probability of a transmission time being i seconds long is denoted by p^u_i for an uplink queue and by p^d_i for the downlink queue.

We denote by W_u and W_d the mean waiting times in a queue of a station (uplink) and the access point (downlink), respectively. We denote by BO the backoff period (in slots) selected by a station. According to the IEEE 802.11 standard and the definition of $CW_{\min}$ in Section 3.1, in the VPP, $BO \sim U(0\ ,\ CW_{\min})$. The slot time is a parameter of the specific IEEE 802.11 standard and is denoted by S.

Although at first glance it seems that a system operated according to VPP differs from a classical polling system, we shall now show that it is *equivalent* to a polling system operating with a combination of the 1-limited and the exhaustive polling regimes[7]. Namely, the system is composed of $N + 1$ queues (N stations and an access point) served by a single server. In the *polling system*, the mean and second moment of the service times at the uplink and downlink queues are denoted by b_u, $b_u^{(2)}$, b_d, and $b_d^{(2)}$, respectively. The mean and variance of the switchover times into each of the uplink queues and into the downlink queue are denoted by r_u, δ_u^2, r_d, and δ_d^2, respectively. The offered load in an uplink queue is given by $\rho_u = \lambda_u b_u$ and the offered load in the downlink is given by $\rho_d = \lambda_d b_d$. The total offered load is given by $\rho = N\rho_u + \rho_d$. The mean of the total switchover time is given by $R = Nr_u + r_d$.

Figure 3 illustrates the operation of the protocol and the equivalent polling system. In order to model the protocol as a polling system, we define the *switchover time* of the server (access point) into an uplink queue (station) as $r_u = CW_{\min}\cdot S + \text{DIFS} + \tau$ (accordingly $\delta_u^2 = 0$). If the access point does not start receiving a frame *during* the switchover time, it will switch into another uplink queue (by sending a CTS). In case a frame is present in the uplink queue, its *service time* is defined only as the part of the transmission time that takes place *after* the end of the contention window. Namely, the service time in the polling system of a frame whose transmission time is t_i is defined as $t_i + BO\cdot S - (CW_{\min}\cdot S + \tau)$. In case this time is negative (this can happen for short frames and short backoff periods), we define the service time as 0 (for an extended description of an analysis using a similar methodology see [12]).

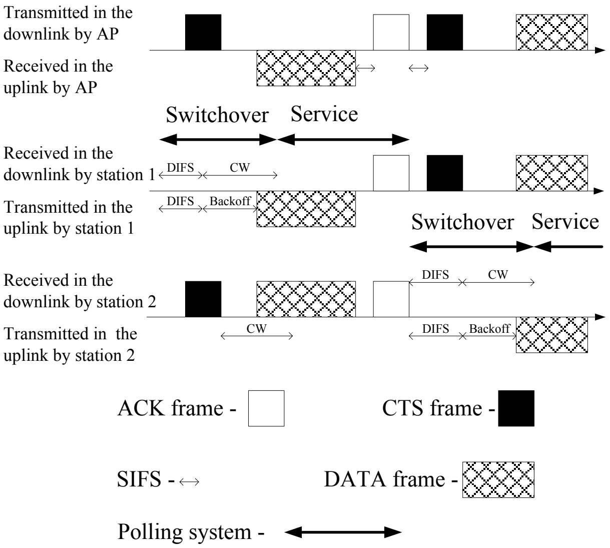

Figure 3: An example of the operation of Virtual Polling Protocol and of the equivalent polling system.

We note that the waiting time (the time until the service *starts*) in the equivalent polling system is *not* equal to the waiting time in a system operated according to the VPP. In order to obtain the mean waiting time under VPP, $CW_{\min}\cdot S/2 + \tau$ has to be deducted from the waiting time in the polling system. This results from the fact that when frames are sent, the actual transmission actually starts during the "switchover" time, as it is defined in the equivalent polling system. According to the above modeling, the mean service time at an uplink queue is defined as follows:

$$b_u = E\left(\max\left[t_i + BO\cdot S - (CW_{\min}S + \tau), 0\right]\right).$$

By deriving the conditional expectations for the case in which $t_i < CW_{min}\cdot S + \tau$ and for the case in which $t_i \ge CW_{min}\cdot S + \tau$, we obtain:

$$b_u = \sum_{i\in M, t_i \le CW_{\min}S+\tau} \frac{p_i^u (t_i-\tau)^2}{2CW_{\min}S} + \sum_{i\in M, t_i > CW_{\min}S+\tau} p_i^u \left((t_i-\tau) - \frac{CW_{\min}S}{2}\right). \tag{1}$$

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[6] An asymmetrical system with non-identical stations can be analyzed in a similar manner.

[7] In a 1-limited regime, only a single customer is served in every server visit. In the exhaustive regime, all customers are served in every visit [8].

$$b_u^{(2)} = \sum_{i \in M, t_i \le CW_{\min} S + \tau} \frac{p_i^u (t_i - \tau)^3}{3CW_{\min} S} + \sum_{i \in M, t_i > CW_{\min} S + \tau} \frac{p_i^u}{3} \Big[\big(t_i - (CW_{\min} S - \tau)\big)^2 + \big(t_i - (CW_{\min} S - \tau)\big)(t_i - \tau) + (t_i - \tau)^2 \Big] . \quad (2)$$

Once the access point completes a cycle, it empties its queue towards the stations. Thus, the access point downlink queue is served according to the exhaustive regime. We define the switchover time into the downlink queue as r_d = SIFS ($\delta_d^2 = 0$) and the service time of a frame residing in that queue as its actual length. Accordingly, $b_d = \sum_{i \in M} p_i^d t_i$ and $b_d^{(2)} = \sum_{i \in M} p_i^d t_i^2$.

Since there are no closed-form results for asymmetrical systems served by a combination of 1-limited and exhaustive regimes [8], we turn to approximate analysis. Groenendijk [5] proposed an approximation for a system with a mixture of exhaustive, gated, and 1-limited service disciplines. According to that approximation:

$$W_d = (1 - \rho_d)\overline{c_r} . \quad (3)$$

$$W_u = \frac{1 - \rho - \rho_u}{1 - \rho - \lambda_u R} \overline{c_r} - \left(\frac{CW_{\min} S}{2} + \tau \right). \quad (4)$$

Where $\overline{c_r}$ is approximately given by

$$\overline{c_r} = \frac{\rho (N \lambda_u b_u^{(2)} + \lambda_d b_d^{(2)}) + R(\rho + N {\rho_u}^2 - {\rho_d}^2)}{2(1 - \rho)\rho_d (1 - \rho_d) + N \rho_u (1 - \rho + \rho_u)} . \quad (5)$$

Notice that due to the difference between VPP and the equivalent polling system, in (4) we deducted $CW_{\min} \cdot S/2 + \tau$ from the waiting time in the uplink. Using (1)-(5) we can now compute the approximate mean waiting times.

We note that the above analysis ignores the rare scenario in which a frame arrives into an empty uplink queue during the time dedicated to the station by the access point, and only then the station initiates the backoff procedure. It seems that the effect of this scenario on the approximate numerical results is insignificant.

Table 1 presents the MAC and PHY parameters of the IEEE 802.11g standard. These parameters have been used in order to derive numerical results. We assume that the data frames are transmitted in the maximum possible rate and that the Bit Error Rate is 0.

Table 1: IEEE 802.11g MAC and PHY Parameters

Parameter	Value
MAC overhead	28 Bytes
PHY overhead	20 µsec
ACK length	14 Bytes
CTS length	14 Bytes

Parameter	Value
SIFS	10 µsec
DIFS	28 µsec
$CW_{\min} \cdot S$	15·9µsec=135 µsec
Rate	54 Mb/s
ACK Rate	24 Mb/s

For the derivation of the numerical results, we assume that there are only two frame types: long frames (1500KB) and short frames (64KB) and that the propagation delay is 10µsec. In the following figures, we denote the probabilities of short frames in the downlink and uplink queues by $p^d{}_S$ and $p^u{}_S$, respectively. The ratio between the number of downlink frames to the number of uplink frames is denoted by *g*.

Figure 4 presents approximate results for a system with a Poisson arrival process composed of 100 stations with $g = 1.2$ and with differing values of $p^d{}_S$ and $p^u{}_S$. The figure presents the mean waiting time as a function of the offered load (per station) in the downlink. It can be seen that, disregarding the frame length distributions, the waiting times in the downlink queue are very low for any load value. This results from the fact that these queues are served in an exhaustive manner. On the other hand, in the *uplink queues* the system approaches the stability limit for arrival rates (to the downlink) of around 160Kb/s (per station). Additional numerical results that explore various design tradeoffs can be found in [2].

At first glance, a saturation rate of around 160Kb/s in the downlink (per station) does not seem very impressing. However, one must remember that we assume that *all the 100 stations constantly receive data in this rate*. This is of course not a practical scenario. We note that other broadband technologies (e.g. [4]) cannot achieve better throughput, in similar conditions.

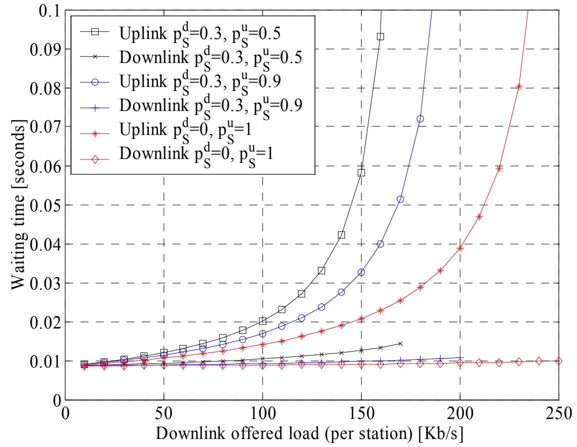

Figure 4: The approximate mean waiting time (in the uplink and downlink queues) in a system operated according to the VPP as a function of the downlink offered load (per station). The number of stations is 100 and *g* = 1.2.

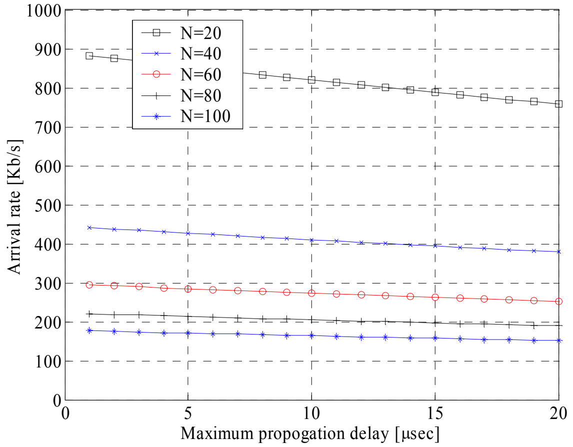

Figure 5: The arrival rate (to the access point of frames destined to a single station) in which the load is 0.8 as a function of the maximum propagation delay. The system is operated according to the VPP, with $p^d{}_S = 0.3$, $p^u{}_S = 0.9$, and *g* = 1.2.

A major concern in the system design is the effect of the relatively large propagation delay on the performance. Thus, we have obtained the relation between the arrival rate and the maximum propagation delay (τ) for a given level of load. Based on the parameters from Table 1, we have computed the arrival rate in which the load in the system is 0.8 (above this load level the waiting times become unacceptable) as a function of the maximum propagation delay. The results are depicted in Figure 5. It can be seen that the arrival rate decrease is moderate for reasonable numbers of station. Recall that the distance between the stations and the Fiber Node as well as the ACKTimeout limitations imply that the propagation delay shall be around 10µsec.

4.2 Comparison of VPP, VPP-TB, and RP

The analytical results, presented above, have been obtained under the assumption of a Poisson arrival process. Since we are also interested in other arrival processes and since the other protocols (VPP-TB and RP) do not easily lend themselves to analytical performance evaluation (see the discussion in [2]), we have developed a Matlab event-based simulation model of the Ca-Fi system. In this model, the arrival of frames from a station's higher layer protocol to the MAC layer is modeled either according to a Poisson arrival process or according to an On/Off arrival process. Upon arrival, frames are scheduled for transmission according to the considered access scheme (i.e., VPP, VPP-TB, and RP in the access point and DCF in the stations). It has been assumed that no station operates in the "power-save" mode.

The performance of the simulation model has been verified by comparing simulation results (obtained for the VPP under the Poisson assumption) to approximate results computed by (1)-(5). It has been found that the simulation results are *very close* to the approximate results. For example, in Figure 6 we present simulation and approximate results in a system operated according to the VPP. The simulation and analytic results have been obtained under the same assumptions (described above, e.g. Table 1). For every offered load value, the results of every simulation experiment have been computed after a period of 100 Ca-Fi seconds. We have computed 95% confidence intervals for the different load values. The widest interval for the uplink waiting time values is 600µsec and the widest interval for the downlink waiting times is 100µsec.

We now compare via simulation the performance of the 3 different protocols both for Poisson and On/Off arrival processes. Figure 6 also presents typical simulation results obtained for a specific scenario for the 3 different protocols in a system with a Poisson arrival process. Considering the performance in the uplink, it can be seen that RP performs *significantly better* than VPP and VPP-TB. *This is due to fact that stations with empty queues do not consume uplink bandwidth*. The price for not consuming bandwidth is doubling the contention window and spending a period of $CW_{\min}$ for reservations every cycle. However, although the contention window is doubled, the Talk-Back feature enables to utilize some of the idle time spent in this window.

The waiting time in the downlink queue in the VPP is one order of magnitude higher than in VPP-TB and RP. In VPP a downlink packet cannot be transmitted before the end of an uplink cycle. On the other hand, in VPP-TB and RP downlink packets are transmitted during the cycle. As can be seen in the figure, these transmissions do not seem to affect the waiting time in the uplink.

In Figure 7 we present simulation results for the same scenario in a system with an *On/Off* arrival process. In that process all the stations and the access point alternate between On and Off states. The time in each state is exponentially distributed. The mean time in the On state is 1 second and the mean time in the Off state is 1.35 seconds. When a station or an access point is in On state, frames arrive at a constant rate. This rate is determined according to the offered load of the specific experiment.

It can be seen that the performance of the 3 protocols is degraded due to the introduction of the On/Off arrival process. This results from the burstiness of the process and the fact that uplink traffic is served in a round robin (1-limited) manner. Although the performance of the specific protocols changes due to the different arrival process, their relative performance is not affected.

To conclude, it seems that the best approach is based on alternation between a few modes. Stations with a very active uplink channel should be polled using VPP-TB while less active stations should be polled using RP. CF-Pollable stations should be polled by the PCF mechanism. Finally, a DCF period should be allocated for new stations. The amount of time dedicated to each of these protocols depends on the traffic patterns.

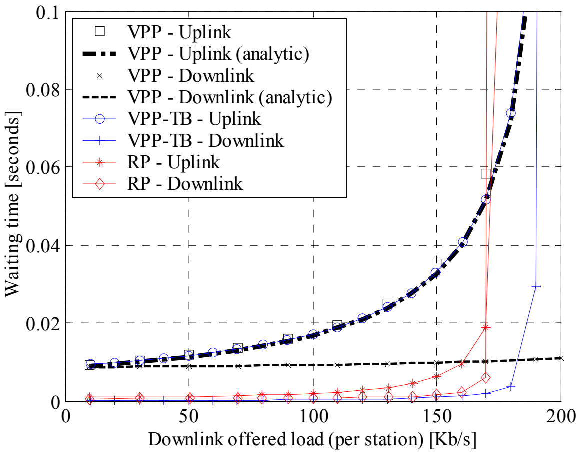

Figure 6: The approximate mean waiting time in a system operated according to the VPP and the average waiting time computed via simulation in systems operated according to VPP, VPP-TB, and RP. The arrival process is Poisson, the number of stations is 100, $p^{d}_{S} = 0.3$, $p^{u}_{S} = 0.9$, and $g = 1.2$.

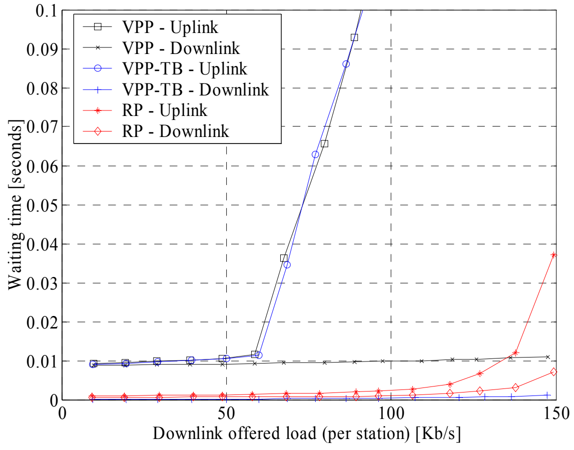

Figure 7: The average waiting time computed via simulation in systems in which the arrival process is On/Off, the number of stations is 100, $p^{d}_{S} = 0.3$, $p^{u}_{S} = 0.9$, and $g = 1.2$.

5. CONCLUSIONS

We have presented a new concept that enables Cellular and Wi-Fi communication over CATV networks. Since wireless broadband access is more efficient when it is based on a polling mechanism rather than on CSMA/CA and since the 802.11 PCF polling mechanism is not widely implemented, we proposed and evaluated new DCF based polling schemes. These schemes enable an access point to poll (in a centralized manner) stations using the DCF mode.

The proposed technology enables instantaneous operations of a few cellular networks, not necessarily at the same standard, on the same CATV infrastructure. It also enables combined cellular and Wi-Fi services. We note that the cost of adapting a CATV network to carry the wireless services (including the cost of the RUs) is relatively low. The deployment of Ca-Fi by a cable service provider that has already deployed CeTV is straightforward. A similar system can be deployed in order to serve wireless stations using other technologies (e.g. IEEE 802.16 - WiMax).

Due to space constraints, we have not presented results regarding the reduction in the number of macrocells due to the deployment of CeTV. Such results are presented in [2] where we study the effect of deploying the CeTV system in a UMTS (Universal Mobile Telecommunications System) cellular network. In [2] we have shown that the deployment of CeTV for indoor coverage can reduce the number of required cells by up to 75%, which may result in considerable cost reduction to the cellular operator. In addition, UMTS over CATV facilitates the provision of high data rate indoor services at a superior quality of service. Such a solution is crucial for UMTS, since it is expected that most of the high rate data services will be used indoors.

Cellular and cable service providers can benefit from the deployment of CeTV, due to cost reductions to the cellular operator and due to potential revenues resulting from the provision of new services by both providers. Yet, a non-technical challenge related to the implementation of CeTV is designing pricing mechanisms that will ease the cooperation between such providers.

Experimental deployments of CeTV are currently ongoing and experimentations with Ca-Fi are expected in the near future. We hope to provide measurements from these experiments in our future works.

Future work will also focus on improving the presented algorithms and designing new protocols tailored for this new medium. For example, we intend to use the measurements from the experimental deployments in order to enable the operation a few stations served by a single RU. In addition, future work will focus on expanding the proposed system to support MIMO technology (IEEE 802.11n). Finally, dealing with emerging standards (such as IEEE 802.11e and IEEE 802.16) and taking advantage of their new characteristics remains an open problem.

6. ACKNOWLEDGMENTS

This research was supported by the ISRC (Israeli Short Range Consortium) funded by the Israeli Chief Scientist office. The research of Gil Zussman was supported by a Marie Curie International Fellowship within the 6th European Community Framework Programme.

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