CeTV and Ca-Fi – Cellular and Wi-Fi over CATV: System Architecture and Performance Evaluation

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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. We show that 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.**

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

I. Introduction

Most of the traffic in cellular communication systems is carried on *Non Line Of Sight (NLOS)* long radio channels. The combination of scarce cellular resources and NLOS radio channels presents complicated design challenges to the radio engineering discipline. These challenges have originated a wide family of radio technologies that have been developed in order to enable proper radio reception under limiting conditions. The usual design philosophy is that poor aerial NLOS channels are inevitable and complex communication and signal processing algorithms are the sole way to improve the radio reception.

In this paper we present a novel concept of *Cellular Communication* over *Community Antenna Television (CATV)* [25][30]. 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 NLOS channels are replaced by the combination of long cables with excellent propagation characteristics and very short aerial LOS channels.

We refer to the system which is based on this proposed concept as *Cellular over CATV* (CeTV). 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 enable a very high quality in-building cellular service. In addition, it will change the linkage between capacity, quality of radio reception, and the size of the cells such that the capacity of the cellular network will be significantly improved.

Following the concept of CeTV, we present a new architecture that enables the transmission of Wi-Fi over CATV (Ca-Fi) [31][32]. In the proposed system, Wi-Fi signals (following any of the standards: IEEE 802.11a/b/g/e/n [14],[15],[16],[17]) 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 internet access to home users, and deployment of IEEE 802.11 networks in hotels and office buildings through the cable network.

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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) [9] (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 a residential or enterprise access point, whereas in the proposed solution there is no need for a cable modem or for an access point. A single access point can be used by the CATV operator to serve several users in different geographic locations.

The proposed concept also differs from the concept of 3-in-1 phone that was proposed as an application scenario of Bluetooth [3]. In that scenario, the cellular phone should become a cordless landline phone, when at home or in an office. According to that scenario the user has to switch between the landline operator and the cellular operator. In addition, a specific Bluetooth enabled cordless phone base unit is required.

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. Among the barriers to implementing the IEEE 802.11 standards at wide areas are the short distance between users, as it is defined by the standards (~200 meters), and the need for mutual listening.

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, due to an increased number of collisions. 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 devices 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. We note that using the switching solution instead of the CSMA/CA solution resembles the transition that took place during the last decade from the legacy Ethernet protocol (CSMA/CD) to switched Ethernet.

The performance of the proposed systems is evaluated analytically and via simulation. First, we evaluate the proposed MAC protocols. Since there is a vast amount of research regarding the DCF and PCF modes (e.g. [2],[5],[6],[23], and references therein), we focus on performance evaluation of the new protocols. We provide an approximate analytic performance evaluation of the Virtual Polling Protocol. These results are derived by modeling the protocol as a specific polling system[1]. Since the performance of the other protocols seems not to be analytically tractable, we have developed a simulation model of the Ca-Fi system. We first 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 the Reservation Protocol. We explore the design tradeoffs of the new protocols and suggest alternating between four protocols based on the characteristics of the stations.

One of the main characteristics of the Ca-Fi system is a relatively long propagation delay[2]. An IEEE 802.11 system parameter that is not explicitly defined in the specifications and that may affect the performance when the propagation delay is long is the ACKTimeout. Therefore, we have performed several experiments with numerous 802.11 devices in order to evaluate their ACKTimeout values. We present the results of these experiments and claim that as long as the distance between the Access Point and the Station is less than 2.5km, the proposed system will function properly.

Finally, we present representative results regarding the effect of deploying the CeTV system in a UMTS (Universal Mobile Telecommunications System) [13] cellular network. Specifically, we present the effect of CeTV on the number of macrocells required in order to meet the capacity and service requirements in a given area. We focus on UMTS since it is emerging as the most widely adopted third generation technology. As such, it is currently being deployed worldwide. Thus, the initial cost of UMTS deployment could be reduced by deploying UMTS over CATV for indoor coverage. We argue that

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[1] A polling system consists of several queues served by a single server according to a set of rules (polling scheme) [20],[28].

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

the deployment of CeTV for indoor coverage can reduce the number of required cells by up to 75%. Furthermore, it seems that most of the high rate data services will be used indoors. It is a major challenge for the network operators to support such rates with the traditional macro coverage planning. Hence, UMTS over CATV facilitates the provision of high data rate services at a superior quality of service.

Obviously, the issues of Cellular and Wi-Fi over CATV have not been thoroughly studied. Yet, some previous works are relevant to our current work. Perhaps, the most closely related work is by Haroun et al. [12] who present experimental results of transmitting 802.11a signal over optical fiber. In addition, Ophir and Bitran [22] present a system that enables transmitting 2.4 GHz 802.11 signals over *in-home* coax networks. That work does not deal with Wide Area Networks or with Cellular Communications and focuses on physical layer aspects.

Numerous papers study MAC enhancements for IEEE 802.11. We are especially interested in enhancements that do not affect the protocol used at the stations and that aim at long propagation delay transmissions. For example, the applicability of IEEE 802.11 standards for outdoor networks with a high propagation delay has been considered in [19]. In addition, [24] proposes a new DCF based polling scheme which does not require to modify the stations. Finally, as mentioned above, 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, [7],[18], and [27]).

The main contributions of this paper are the introduction of novel system architectures for Cellular and Wi-Fi communication over CATV as well as the design and performance evaluation of new MAC protocols that are required at an access point deployed in a Wi-Fi over CATV network.

This paper is organized as follows. In Section II we briefly describe the CATV and IEEE 802.11 technologies. Section III presents the concept of wireless over CATV and describes the physical layer aspects. In Section IV, we describe a few alternatives for MAC layer design required in order to use Wi-Fi over CATV. In Section V, we evaluate the performance of the proposed Ca-Fi MAC protocols and present results regarding the ACKTimeout as well as the effect of CeTV on the number of macrocells required in a UMTS system. Section VI summarizes the main results and discusses open problems and future research directions. We note that a list of abbreviations used throughout this paper is provided in Table 6 in Appendix I.

II. Legacy Technologies

A. 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 from the node are arranged in a tree topology and carry the signals from the node to the indoor subscribers. Each node serves 1500 to 2000 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 has emerged as the preferred CATV architecture, since it can readily support bi-directional communication and signaling between the subscriber unit and the HE. Bi-directional communication is achived 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 is higher than 1.2GHz (see Table 1), where the linear amplifiers along the network induce the 860MHz upper limit.

Table 1
CATV Frequency Limits

Network element	Frequency limit
Fibers	2.5GHz
Cables	2.0GHz
Linear amplifiers	860MHz or less (according to the service)
Combiners/Splitters	1.2GHz

B. IEEE 802.11

IEEE 802.11 defines two major topologies: infrastructure and ad hoc. In an infrastructure topology stations (STAs) communicate with an Access Point (AP). In an ad hoc topology, the stations communicate among themselves. In this paper we focus on the infrastructure topology. The 802.11 MAC supports two modes of operation: the *Distributed Coordination Function (DCF)* and the *Point Coordination Function (PCF)*.

The DCF mode, which is illustrated in Figure 1, is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). Each station maintains a Contention Window (CW) that is used to determine the time (in slots) a station 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 *DIFS (Distributed Interframe Space)* period.

If the backoff counter expires and the medium is still free, the station begins to transmit. In case of a collision, the station randomly picks a new backoff period from its contention window, which increases in a binary exponential fashion, and then, attempts to gain control of the medium again. Due to the collisions and the binary backoff mechanism, there are no transmission guarantees. Upon successful reception of a frame, the receiving station immediately acknowledges the frame reception by sending an acknowledgement frame (ACK) within a *SIFS (Short Interframe Space)* period. In case an ACK is not received within an ACKTimeout, the transmitting station determines that the frame has been lost.

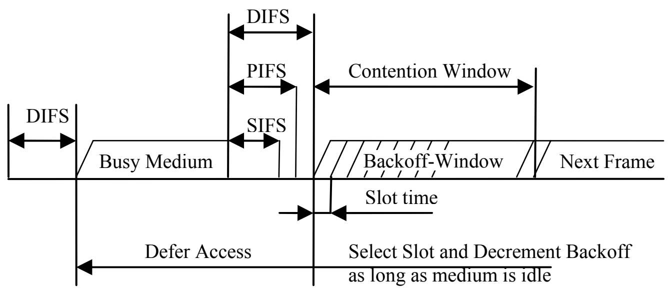

Figure 1. IEEE 802.11 DCF operation

In addition to the physical channel sensing, the 802.11 MAC protocol implements a Network Allocation Vector (NAV), whose value indicates to each station the amount of time that remains before the channel will become idle. The NAV is updated according to a duration field contained in all transmitted frames. The NAV is thus referred to as a virtual carrier sensing mechanism. The MAC uses the combined physical and virtual sensing to avoid collisions.

The protocol described above is a two-way handshake mechanism. In addition, the MAC also contains a four-way frame exchange protocol. This protocol requires that a station sends a special, Request-To-Send (RTS) message, instead of the actual data frame. In response, if the destination sees that it is appropriate, it sends a Clear-To-Send (CTS) message within a SIFS period. This message instructs the requesting station to start the frame transmission immediately. The main purpose of the RTS/CTS handshake is to resolve the hidden node problem.

The use of the RTS/CTS mechanism is controlled by the RTSThreshold attribute, which is set on a per-station basis. This attribute allows stations to be configured to use RTS/CTS either always, never, or only on frames longer than a specified length. However, the default value of RTSThreshold is the maximum frame length which is longer than the longest Ethernet frame. This implies that by default RTS/CTS is not used.

The *Point Coordination Function* (PCF) provides contention-free frame transfer. The Point Coordinator (PC), which is co-located with the Access Point, generates beacon frames, which start the Contention Free Period (CFP), at regular intervals. Thus, every station knows when the next beacon frame will arrive. In the PCF mode, a PC polls the stations one after another by sending Contention-Free Poll (CF-Poll) messages. If the polled station has a pending frame, it is sent in the response message. If the PC received no response from a polled station after waiting for *Priority Interframe Space (PIFS)*, it polls the next station, or ends the CFP. A specific control frame, called CF-End, is transmitted by the PC, to signal the end of the CFP.

All 802.11 stations inherently obey the medium access rules of the PCF. However, it is not mandatory for a station to be able to respond to a CF-Poll received from a PC. A station that is able to respond to CF-Polls is referred to as being CF-Pollable. *In practice, most 802.11 stations are not CF-Pollable.*

III. Wireless Over CATV – Physical Layer

A. 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 2. 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. We shall refer to this device as *RU (Residential Unit)* and it can be seen in Figure 3.

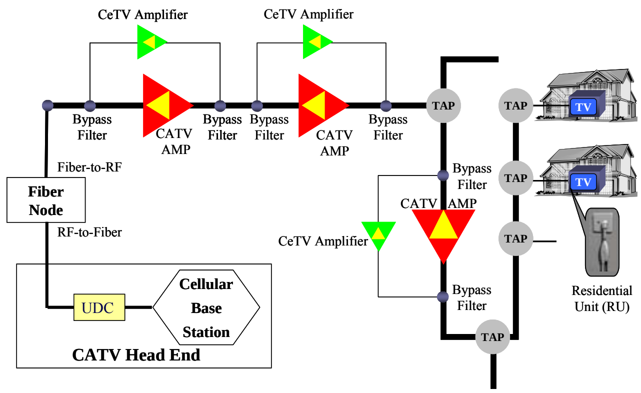

Figure 2. The CeTV system architecture

Figure 3. The RU (Residential Unit)

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). Hence, the cellular uplink and downlink bands 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 1200 MHz. 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 1200 MHz. The modification enables bi-directional free linear flow of the frequency converted cellular radio signals through the CATV network.

Each RU can transmit up to 1mW of signal power to serve an indoor area of 100-150 sq. meters. Similar devices are available for outdoor use. They can be located along the streets (3 to 5 meters above the ground) and can serve LOS customers at distances of up to 150 meters. In our experiments, density of 10-20 devices/sq. km. was found to supply comprehensive outdoor coverage at urban areas.

We note that, in the proposed system the total radio path of the cellular signal is actually longer than in common existing cellular topologies, but its aerial portion is much shorter. This promises better radio reception at the cellular phones.

B. 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. Transmitting Wi-Fi signals over the CATV infrastructure enables the establishment of *centralized managed* wireless Wide Area Network (WAN) access. The Ca-Fi system is implemented by allocating a portion of the newly generated bandwidth to carry Wi-Fi signals. As in CeTV, the system must work with legacy Network Interface Cards. Therefore, 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 IV). Additional elements, which are required for the operation of the physical layer, also support these MAC enhancements. Moreover, as will be shown in Section V, the ACKTimeout, defined by the different vendors, usually does not allow a propagation delay corresponding to more than 2.5km. Therefore, the IEEE 802.11 Access Points are deployed in the Fiber Nodes, whose distances to the subscribers' premises are 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 (desirably in different times). However, TDD access may cause oscillations at the active elements of the network, and in particular 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 solution at the RUs. The switching process can be controlled either by an activity detector 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 controlled switches enable the separation of single users or groups of users by blocking their reception and/or transmission capability. In other words, 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.

IV. Wi-Fi over CATV – MAC Layer

The CATV WAN topology introduces new obstacles that are not accounted for by the IEEE 802.11 standards. In this section we briefly describe these obstacles. Then, we present a few possible modifications to the MAC protocol used by the access point that can be utilized in order to overcome these obstacles. We emphasize that these modifications impose changes only to the design of the access points installed by the CATV operator.

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. 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 (from the Fiber Node to the users) and uplink (from the users to the Fiber Node). 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 handshake. However, the RTS/CTS mechanism is inefficient when the number of hidden stations is high. 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 III.B) and that are compatible with stations operating in the DCF mode. 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 (i.e. legacy DCF which will be used mostly for authentication and association of new stations).

A. 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 (described in Section II.B). 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. Thus, non-CF-Pollabale stations will not interfere with the operation of the Contention Free Period.

We note that the authors of [19] mention that the PCF protocol seems to be infeasible in networks with high propagation delays (higher than 10μsec). Yet, we argue that a minor manipulation in the PCF protocol 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 PIFS period, following a transmission from the access point, then the access point shall resume control and may transmit its next frame (after a PIFS period from the end of its last transmission). However, a high propagation delay may lead the access point to mistakenly assume that the polled station did not respond within the PIFS period. Thus, 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 maximal radius of the CATV network (up to 2km, i.e., ~10 μsec).

B. 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 mechanism utilizes the PHY switching system (described in section III.B) to poll a specific station by selectively transmitting CTS messages to all other stations. Although the medium is governed by the standard DCF mode, the proposed protocol provides transmission guarantees with *contention free frame transfer*, similarly to the PCF protocol.

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 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 4 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 (CW). Upon receiving this CTS message all stations update their 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 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.

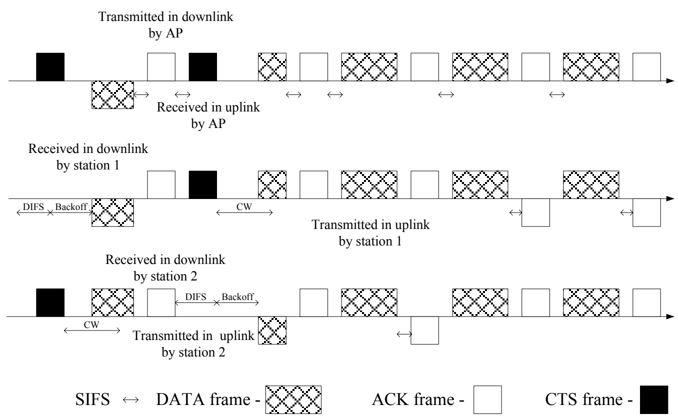

Figure 4. An example of the operation of the Virtual Polling Protocol in a network with an access point and 2 stations

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 minimal value[4]. We denote the value of the minimal contention window by $CW_{\min}$.[5]

C. Talk-Back enhancement of the VPP (VPP-TB)

We note that 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).*

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[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.

[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] As mentioned in Section II.B, 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.

In this version of the protocol, 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. The frames are sent according to First-In-First-Out (FIFO) order and are not necessarily sent to the station that sent the last uplink frame. As will be shown is Section V, the proposed enhancement not only improves the operation of the protocol but is also essential in the Reservation Protocol described below.

D. 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 described above). The advantage of this protocol is that during every cycle *only stations that have pending frames transmit*. The access point uses the activity detection capability at the RUs in order to determine which stations have pending frames. Then, it polls (using the Virtual Polling Protocol) only these stations. Similarly to the Virtual Polling Protocol, this protocol requires modifications to the access point MAC protocol and it operates with stations using the regular DCF mode.

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 shall refer to this contention window 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 initiate a cycle and poll these stations using the Virtual Polling Protocol (VPP) described in Section IV.B. Namely, it will send CTS messages only regarding stations which tried to transmit during the reservation phase.

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.

E. Contention Period

To allow new stations to complete 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). All nodes are hidden from each other. Thus, we partially solve the hidden node problem by *broadcasting* every bit received in the uplink to all the stations except the transmitting station. As in the VPP, the broadcast is done disregarding the frame's content.

V. PERFORMANCE EVALUATION

In this section we present analytic and simulation results regarding the Ca-Fi MAC protocols (VPP, VPP-TB, and RP). We focus on the new protocols, since the legacy protocols (PCF and especially DCF) have been thoroughly studied in the past (see [2], [5], [6], [23]). We note that throughout the analysis we assume that the RTS/CTS handshake is disabled. Then, we present results of experiments conducted with various 802.11 devices in order to validate that the long propagation delay does not degrade the performance of the Ca-Fi system. Finally, the effect of the CeTV system on the number of required macrocells in a UMTS cellular network is briefly discussed.

A. Virtual Polling Protocol (VPP)

In this section we first provide an analytical model of the Virtual Polling Protocol and derive approximate results under the assumption of a Poisson arrival process. Then, we present simulation results and show that the analytic and the simulation results are very close.

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 transmis-

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

sion 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, it is clear that 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. p^u_i and p^d_i are simple functions of the probability that a frame will include a given number of bytes.

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 IV.B, in the proposed virtual polling protocol, $BO \sim U(0\ , CW_{\min})$. The slot time is one of the parameters of the implemented IEEE 802.11 standard and shall be 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]. In the description of the system, we mainly follow the notation of Takagi [28]. 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, $\delta_u^{\ 2}$, r_d, and $\delta_d^{\ 2}$, 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 5 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 $CW_{\min}{\cdot}S$ + DIFS + τ (i.e. $r_u = CW_{\min}{\cdot}S + \text{DIFS} + \tau$ and $\delta_u^{\ 2} = 0$). 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 [29]).

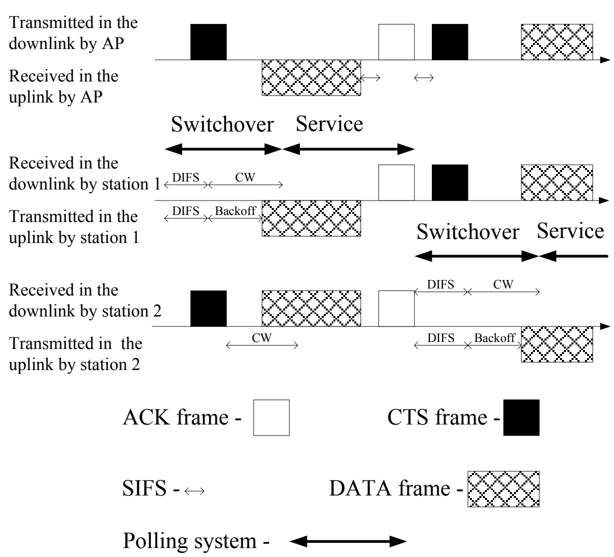

Figure 5. An example of the operation of Virtual Polling Protocol and of the equivalent polling system

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

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[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 [20],[28].

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 of the service time at an uplink queue is defined as follows:

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

Since $BO \sim U(0\ , CW_{min})$, the conditional expectation for the case in which $t_i < CW_{min}\cdot S + \tau$ is:

$$E\left(\max\left[t_i + BO\cdot S - (CW_{\min}S+\tau),0\right]\middle| t_i < CW_{\min}S+\tau\right) = \frac{CW_{\min}S+\tau-t_i}{CW_{\min}S}\cdot 0 + \frac{t_i-\tau}{CW_{\min}S}\cdot\frac{t_i-\tau}{2}$$

Similarly, by obtaining the conditional expectation for the second case, we derive the mean the second moment of the service time at an uplink queue:

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

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

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 master's queue as SIFS (i.e. r_d = SIFS and $\delta_u{}^2 = 0$) and the service time of a frame residing in that queue as its actual length. Accordingly, $b_d = \sum_{i=1}^m p_i^d t_i$ and $b_d^{(2)} = \sum_{i=1}^m p_i^d t_i^{\,2}$.

Since there are no closed-form results for asymmetrical systems served by a combination of 1-limited and exhaustive regimes [20], we turn to approximate analysis. Groenendijk [11] 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 at the access point and the stations, for any given frame length distributions and arrival rates.

We note that the above analysis ignores the scenario in which a frame arrives into an empty uplink queue during the time dedicated to the station by the access point (the length of this period is $CW_{\min}$), and only then the station initiates the backoff procedure. In that case although a queue in not empty, a frame may not be transmitted during the time dedicated to the station. Since we are interested in approximate results, it seems that the effect of this rare scenario on the numerical results is insignificant.

Table 2 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 maximal possible rate, that the ACK frames are transmitted at a rate of 24Mb/s, and that the Bit Error Rate is 0.

For the derivation of the numerical results, we assume that there are only two frame types: long frames (1500KB) and short frames (64KB). Using the parameters defined in Table 2 and assuming that the propagation delay is 10μsec, yields the total transmission time (including overheads, propagation delays, SIFS, and ACK) of both types. Accordingly, the total transmission time of a short frame is: t_S = 88μsec, and the total transmission time of a long frame is: t_L = 301μsec. In the following figure, 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.

Table 2
IEEE 802.11 MAC AND PHY PARAMETERS

Parameter	Value (802.11g)
MAC overhead	28 Bytes
PHY overhead	20 μsec
ACK length	14 Bytes
CTS length	14 Bytes
SIFS	10 μsec
DIFS	28 μsec
$CW_{min} \cdot S$	15·9μsec = 135 μsec
Rate	54 Mb/s
ACK Rate	24 Mb/s

Figure 6 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 property 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). Recall, that the uplink queues are served in a 1-limited regime and that according to our assumptions, most of the data is transmitted in the downlink.

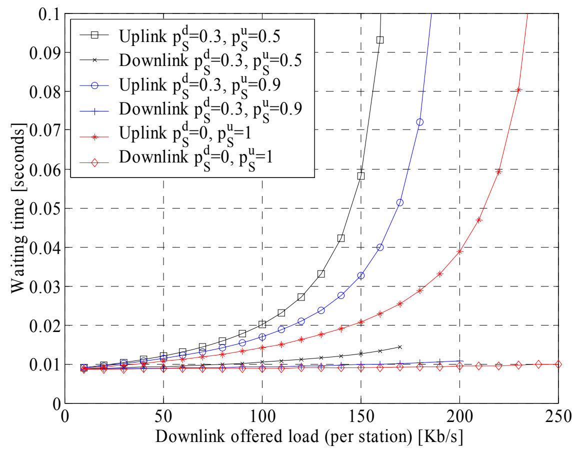

Figure 6. The mean waiting time (in the uplink and downlink queues) in a system operated according to the VPP as a function of the downlink offered load (per station). The number of stations is 100 and g = 1.2

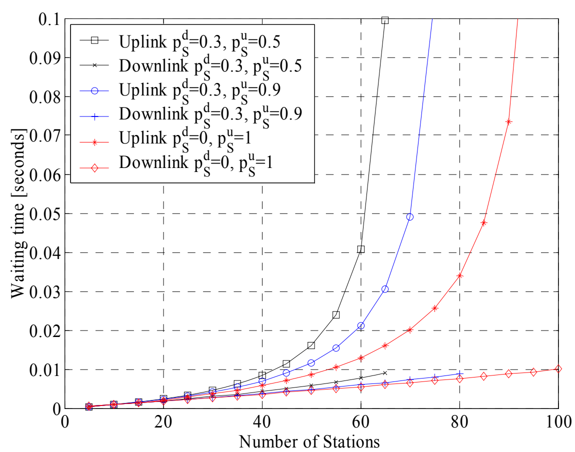

Figure 7. The mean waiting time in a system operated according to the VPP as a function of the number of stations. The arrival rate to the access point of frames destined to a single station is 256Kb/s and g = 1.2

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. [8]) cannot achieve better throughput, in similar conditions.

In order to better understand the effect of the number of active stations, we present in Figure 7 approximate results for a system with a Poisson arrival process in which the downlink offered load (per station) is 256Kb/s. The figure presents the mean waiting time as a function of the number of stations. It can be seen that the waiting times in the downlink queue increase almost linearly with the number stations. The waiting times in the uplink queue start to increase when the number of simultaneously active stations exceeds 40.

We further study the tradeoff between the number of stations and the downlink offered load by computing the arrival rate to a downlink queue that causes a given level of load for a given number of stations. We denote by α the arrival rate (in bits/sec) of packets destined to a single station. By definition $\lambda_u = g\lambda_d/N$ and $\lambda_d = \alpha N/l_d$, where l_d is defined as the average downlink packet length (in bits). The load in the system is defined as

$$L = \rho + \lambda_u R = N\rho_u + \rho_d + \lambda_u (Nr_u + r_d) = N\lambda_u b_u + \lambda_d b_d + \lambda_u (Nr_u + r_d) .$$

Thus,

$$\alpha = \frac{Lgl_d}{N\left(b_u + gb_d + r_u\right) + r_d} . \tag{6}$$

Figure 8 presents α (the arrival rate per station) in which the load in the system is 0.8 as a function of N (number of the stations) for differing values of $p^d{}_S$ and $p^u{}_S$, and for g=1.2. Above the load level of 0.8, the delays become unacceptable. It can be seen that disregarding the frame length probabilities, downlink rates of 1Mb/sec can be maintained for a population of around 20 *simultaneously* active stations.

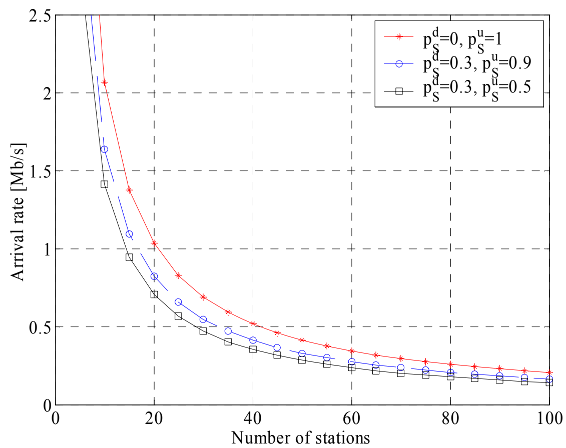

Figure 8. The arrival rate (to the access point of frames destined to a single station) in which the load is 0.8. The system is operated according to the VPP and g = 1.2

As mentioned in Section V.C, a major concern in the system design is the effect of the relatively large propagation delay on the performance. Similarly to the derivation of (6), we have obtained the relation between the arrival rate (α) and the maximum propagation delay (τ) for a given level of load. We note that in this case t_S, t_L b_u, b_d, and r_u are all functions of τ.

Based on the parameters from Table 2, we have computed the arrival rate in which the load in the system is 0.8 as a function of the maximum propagation delay. The results are depicted in Figure 9. It can be seen that the arrival rate decrease almost linearly with the propagation delay and the 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 (will be discussed in Section V.C) imply that the propagation delay shall be around 10μsec. It can be seen the system is quite insensitive to deviations from this value.

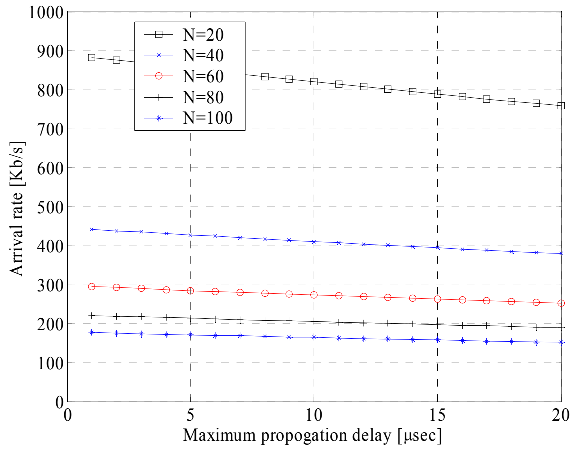

Figure 9. The arrival rate (to the access point of frames destined to a single station) in which the load is 0.8 as a function of the maximum propagation delay. The system is operated according to the VPP, with $p^d{}_S = 0.3$, $p^u{}_S = 0.9$, and $g = 1.2$

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 Section IV.D below), we have developed a Matlab simulation model of the Ca-Fi system. 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, Figure 10 compares the simulation results to the analytic results in a system operated according to the VPP. For every offered load value, the results of every simulation experiment have been computed after a period of 100 CaFi seconds. We have computed 95% confidence intervals for the different load values. The widest interval for the uplink delay values is 600µsec (which is narrower than the mark on the figure) and the widest interval for the downlink delay is 100µsec.

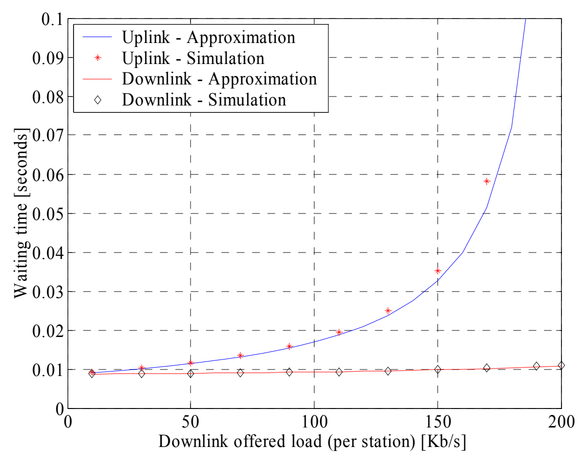

Figure 10. The approximate mean waiting time and the average waiting time computed via simulation in a system operated according to the VPP. The number of stations is 100, $p^d{}_S = 0.3$, $p^u{}_S = 0.9$, and $g = 1.2$

B. Comparison between VPP, VPP-TB, and RP

In this section we compare the performance of the 3 different protocols (VPP, VPP-TB, and RP) both for Poisson and On/Off arrival processes. Before we proceed, we shall briefly describe the obstacles in the analytical modeling of VPP-TB and RP.

In VPP-TB, after every transmission in the uplink, the access point can transmit in the downlink. If a station transmits a frame that is significantly shorter than $CW_{\min}$, the access point can use the remaining idle time for the transmission of the downlink frame.

Analytical performance evaluation of VPP-TB leads to modeling the system as a polling system in which the server alternates between the queues in the following manner 1→D→2→D→…→N→D→1.. (where D is the downlink queue at the access point). This is actually a *star* polling system in which all queues are served according to the 1-limited regime. Manfield [21] has studied such a system in which the D queue is served according to the exhaustive regime and all other queues are served according to the 1-limited regime. Giannakouros and Laloux [10] have extended the analysis of such a system to allow queues 1 to *N*, to operate according to the gated or exhaustive regimes. Finally, Boxma et al. [4] have presented a pseudoconservation law for a system with polling tables. The system discussed above is a specific case of the systems analyzed in [4]. However, the authors of [4] mention that in order to carry out an exact analysis, they impose the restriction that stations with a 1-limited service strategy are served only once a cycle.

To conclude, it seems that there are no closed form results for a star polling system in which all queues are served according to the 1-limited regime. Due to the complexities in the analytic performance evaluation of such a system, the evaluation of this system has been done via simulation.

In the Reservation Protocol (RP) the contention window dedicated to each station is $2CW_{\min}$. Therefore, there is a chance that the channel will be idle for a significant amount of time, after an uplink frame transmission. Thus, the Talk-Back enhancement is used, thereby raising the same complexities discussed above. Numerous reservation protocols have been analyzed in the past (see the review in [1]). However, the proposed protocol combines reservation elements with a 1-limited star polling system, and therefore, its performance has also been analyzed via simulation.

Figure 11 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 $CW_{\min}$ for reservations. However, although the contention window is doubled, the Talk-Back feature enables to utilize some of the idle time spent in this window.

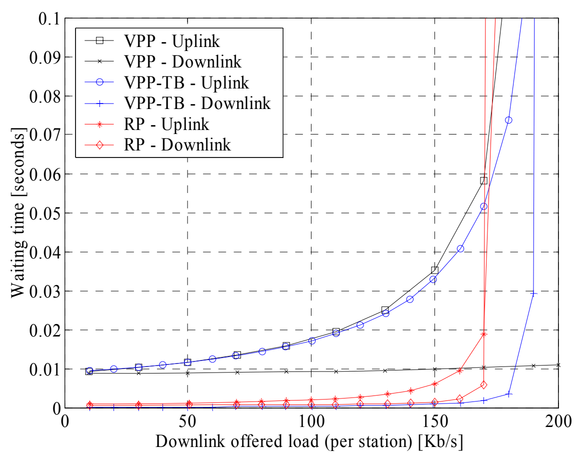

Figure 11. The average waiting time computed via simulation in systems operated according to VPP, VPP-TB, and RP. The arrival process is Poisson, the number of stations is 100, $p^d{}_S = 0.3$, $p^u{}_S = 0.9$, and $g = 1.2$

The waiting times in VPP and VPP-TB are very similar, mostly due to the fact that the Talk-Back feature does not assist the packets waiting in the uplink queues. 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 order to demonstrate that the above observations also hold for other arrival processes, we present in Figure 12 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.

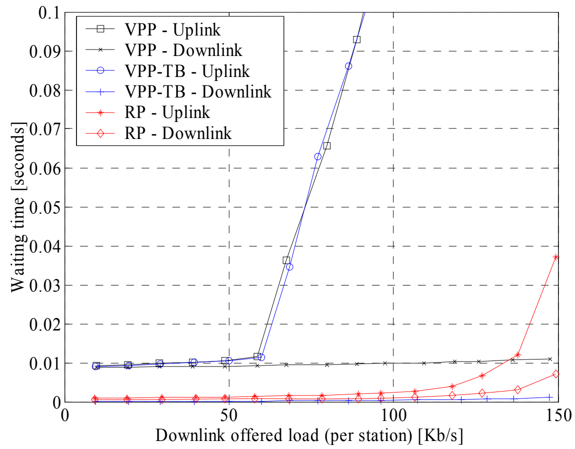

Figure 12. The average waiting time computed via simulation in systems operated according to VPP, VPP-TB, and RP. The arrival process is On/Off, the number of stations is 100, $p^d{}_S = 0.3$, $p^u{}_S = 0.9$, and $g = 1.2$

When comparing Figure 11 to Figure 12, 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. Accordingly, large batches of packets that arrive almost together may incur large delay (as opposed to single packets whose arrival times are exponentially distributed as in the Poisson arrival process).

Although the performance of the specific protocols changes due to the different arrival process, their relative performance is not affected. It can be seen that RP still significantly outperforms VPP and VPP-TB in the uplink and that in the downlink VPP is still worse than VPP-TB and RP. Several additional simulation experiments point out that these observations are also valid for different packet length distributions.

To conclude, it seems that the best approach for the operation of the Ca-Fi system is based on alternation between a few modes. Since the Reservation Protocol may unnecessarily consume bandwidth when operated with stations with a very active uplink channel, such stations should be polled using VPP-TB. On the other hand, less active stations should be polled using RP. CF-Pollable stations shall be polled by the PCF mechanism, which is the most efficient mode for such stations. Finally, a DCF period should be allocated for new stations.

C. Long Propagation Delay and ACK Timeout

One of the challenges in implementing a long distance WiFi system (like Ca-Fi) is dealing with the ACKTimeout. According to the IEEE 802.11 standards an acknowledgment message (ACK) should be sent from a receiving station to a transmitting station whenever a data frame is received without any errors. The ACK should arrive to the transmitter within a certain period (ACKTimeout), otherwise the transmitter concludes that the data frame had been lost and retransmits it. If the propagation delay is longer than the ACKTimeout, the transmitting station may mistakenly conclude that the packet has been lost. Recall that the value of the ACKTimeout is not defined in the IEEE 802.11 specifications.

In order to recognize the distance limitations resulting from the ACKTimeout mechanism, we have conducted several experiments with different Network Interface Cards based on different chipsets. In these experiments the cards were tested over different distances implemented using optical fiber. A Linux machine was used as an Access Point and for measuring the performance of the different cards.

Table 3 summarizes the results of the experiments. For each card it presents the maximum distance in which the ACKTimeout does not expire prior to receiving the ACK. It can be seen that the ACKTimeout defined in the cards that are provided by most of the major vendors allows transmitting frames over a distance of a least 2.5km. Since the Fiber Node is usually closer to the stations, we conclude that the ACKTimeout is not an obstacle to the deployment of the Ca-Fi system.[8]

We note that it can be seen in Table 3 that the maximum distance of two cards based on the Broadcom chipset is 1km. We found that even in such a case, a simple enhancement to the algorithm used by the access point can enable the transmission to a distance of up to 3.5km. This enhancement does not require any modifications to the cards or the stations. The enhancement has been tested. It is briefly described in Appendix II.

[8] In case the distance between a specific Fiber Node and the stations is greater than 2.5km, the CATV network operator will initially not provide Ca-Fi service to customers connected to this node.

Table 3
THE MAXIMUM DISTANCE IN WHICH DIFFERENT CARDS CAN OPERATE (BASED ON THEIR ACKTIMEOUT)

Network Interface Card	Chipset	Max Distance
NETGEAR WG311	Atheros	2.5km
NETGEAR WG311T	Atheros	2.5km
D-Link DWL-G510	Marvell	3.5km
D-Link DWL-G520	Atheros	2.5km
D-Link DWL-G520+	TI	3.5km
LinkSys WMP54G	Broadcom	1km
LinkSys WMP54GS	Broadcom	2.5km
TRENDnet TEW-403PI	Broadcom	1km
TRENDnet TEW-423PI	TI	3.5km
Edimax 7128g	Ralink	3.5km
LevelOne WNC-0301	Marvell	3.5km
D-Link DWL-520+ (802.11b)	TI	3.5km
Intel PRO/Wireless 2100 (802.11b)	Intel	3.5km

D. CeTV and UMTS

The introduction of a CeTV system will have two major impacts on the deployment of UMTS macrocells: (i) indoor coverage will be attained mainly through the CeTV system. Consequently, transmission from outdoor macrocells will not need to penetrate walls in order to provide indoor coverage, and (ii) indoor traffic that will be carried via the CeTV system will not contribute to the noise rise in the macrocells. Consequently, the coverage area of macrocells, which would be less loaded, will increase.

Here, we present numerical results of a simple, yet representative, analysis that considers the above impacts of the CeTV system and estimates its benefits. Our figure of merit is the reduction in the number of UMTS macrocells that are required in order to meet the capacity and service requirements both outdoors as well as indoors. We note that due to space limitations, some technical details of the computations are omitted.

We consider an area of 65 square km with a population of 2297 users per square km[9]. For the ease of the analysis, we assume that the population is uniformly distributed in the considered area. We also assume that 35% of the UMTS users are located indoors. We assume the COST 231–Hata propagation model [8]. However, in order to distinguish between indoor and outdoor users, we assume an additional 12dB penetration loss for indoor users.

We have based our numerical analysis on the well-known uplink quality equation and on the downlink pole equation (see for example, [13],[26]). We iterated on the cell range and at each iteration, if the load factor was higher than the set limit of 50%, mobile users were removed from the cell by reducing the cell range. At the end of the uplink and downlink iterations, the cell range was determined and the corresponding number of macrocells at the considered area was established.

We have compared the number of required macrocells with and without CeTV. When CeTV is deployed, the analysis assumes that 35% of the users are removed from the system and that the path loss to the remaining users does not include the 12dB penetration loss. It turns out that most of the reduction in the number of cells results from the reduction in the path loss, whereas the reduction in the number of users has an insignificant effect.

Figure 13 presents representative numerical results regarding the number of required UMTS macro-cells for two usage scenarios that are expected at launch and in year 2010. The usage scenarios are described in Table 4. For each scenario, we present the number of cells for two cases: (i) both outdoor as well as indoor coverage are obtained through macrocells, and (ii) outdoor coverage is obtained through macrocells and indoor coverage is obtained through the CeTV network. From

Figure 13, it is easy to see that the deployment of UMTS over CATV for indoor coverage has the potential to significantly reduce the number of required macrocells (e.g., from 207 to 46 macrocells at launch).

Table 4
TRAFFIC LOADS AT TWO USAGE SCENARIOS

	Mini-Erlangs	
Service	Launch	2010
Voice	0.78	22.6
WWW@64 kbps	1.29	105.6
WWW@144 kbps	0.0123	3.15
WWW@384 kbps	0.00768	0.28

[9] The area characteristics correspond to an area surrounding Oxford, UK.

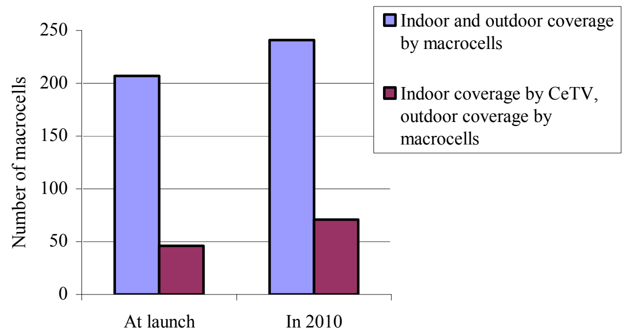

Figure 13. The number of macrocells in a UMTS network with and without CeTV deployment

It is clear that not all indoor users will use the CeTV solution. Therefore, Table 5 presents the indoor coverage probabilities in case only some of the indoor users use CeTV (i.e. 20%, 50%, or 80% of the indoor users use CeTV) for different number of cells. Notice that in all cases the outdoor coverage is higher than 95%.

Table 5
INDOOR COVERAGE AS A FUNCTION OF THE NUMBER OF CELLS AND THE CETV USAGE

Number of cells	20% usage	50% usage	80% usage
46	38%	61%	84%
100	58%	74%	89%
150	78%	86%	94%
207	>95%	>95%	>95%

VI. CONCLUSIONS

We have presented a new concept that enables Cellular and Wi-Fi communication over CATV networks. The implementation of the cellular system (CeTV) is related only to the physical layer, and therefore, any type of known or emerging cellular standard can benefit from it. The proposed technology enables instantaneous operations of few cellular networks, not necessarily at the same standard, on the same CATV infrastructure. It also enables combined cellular and Wi-Fi services.

The CATV infrastructure cannot immediately carry the Wi-Fi signals. Hence, we developed a new technology composed of frequency converters, by-pass amplifiers, and a switching system. Since wireless broadband access is more efficient when it is based on a polling mechanism rather than on a CSMA/CA MAC and since the 802.11 PCF polling mechanism is not widely implemented, we proposed new DCF based polling schemes. These schemes enable an access point to poll (in a centralized manner) stations using the DCF mode. We have evaluated the proposed protocols and concluded that using a combination of PCF, DCF, the proposed Virtual Polling Protocol with Talk-Back (VPP-TB), and the Reservation Protocol (RP) will yield best results. The amount of time dedicated to each of these protocols depends on the traffic patterns and the stations' characteristics.

We note that the cost of adapting a CATV network to carry the wireless services is relatively low. In addition the cost of the unit that should be connected to the cable socket (RU) is negligible. One of the main advantages of deploying CeTV is a drastic reduction in the number of required macrocells, which may result in considerable cost reduction to the cellular operator.

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. We intend to use the measurements from the experimental deployments in order to enable the operation a few stations served by a single RU and to enhance the MAC algorithms. Finally, dealing with emerging standards such as IEEE 802.11e and taking advantage of their new characteristics remains an open problem.

VII. ACKNOWLEDGMENTS

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APPENDIX I

Table 6
A LIST OF ABBREVIATIONS

Abbreviation	Meaning
AP	Access Point
CATV	Community Antenna Television
CF	Contention Free
CFP	Contention Free Period
CTS	Clear to Send
DCF	Distributed Coordination Function
CSMA/CA	Carrier Sense Multiple Access / Collision Avoidance
CW	Contention Window
DIFS	Distributed Interframe Space
FDD	Frequency Division Duplex
FN	Fiber node
HE	Head End
HFC	Hybrid Fiber Cable
LOS	Line of Sight
NAV	Network Allocation Vector
PC	Point Coordinator
PCF	Point Coordination Function
PIFS	Priority Inteframe Space
RP	Reservation Protocol
RTS	Request to Send
RU	Residential Unit
SIFS	Short Interframe Space
STA	Station
TDD	Time Division Duplex
UDC	Up-Down Converter
UMTS	Universal Mobile Telecommunications System
VPP	Virtual Polling Protocol
VPP-TB	Virtual Polling Protocol with Talk-Back

APPENDIX II

In Section V.C we have discussed the maximum transmission distance of different Network Interface Cards. It has been mentioned that a simple enhancement to the algorithm used by the access point can enable the transmission to a distance of up to 3.5km even for cards whose maximum distance is 1km.

The main idea is to send a shorter ACK than the one expected by the station, thereby leaving more time for the large propagation delay. At the connection establishment phase the station and the access point negotiate a few parameters. At that phase, the access point can force the station to use a long preamble and to calculate its ACK Timeout based on this preamble. On the other hand, the access point can transmit the ACKs using a short preamble freeing the difference between the two preamble durations for additional propagation delay. The operation of this mechanism is demonstrated in Figure 14.

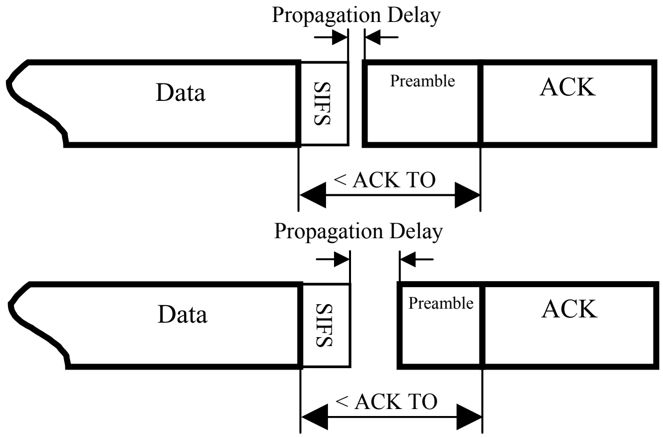

Figure 14. Using a short preamble in order to allow for a long propagation delay

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