Computer Standards & Interfaces 31 (2009) 816–829

Contents lists available at ScienceDirect

Computer Standards & Interfaces

journal homepage: www.elsevier.com/locate/csi

A new QoS-aware TDMA/FDD MAC protocol with multi-beam directional antennas

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ARTICLE INFO

Article history:
Received 14 November 2007
Received in revised form 10 July 2008
Accepted 28 September 2008
Available online 18 November 2008

Keywords:
TDMA
Directional antennas
MAC
QoS
WATM

ABSTRACT

With the ever-increasing demand for wireless real-time services and continuing emergence of new multimedia applications especially for mobile users, it is necessary for the network to support various levels of quality of service (QoS) while maximizing the utilization of scarce and expensive wireless channel resources. Considering this fact, a new TDMA/FDD MAC protocol integrating a novel QoS management algorithm and multi-beam Directional Antennas (DAs) to efficiently exploit wireless resources has been developed and presented in this paper. It supports all ATM CBR, VBR, ABR and UBR service classes by adopting a well-managed dynamic guarantee-based QoS scheduling algorithm. The work mainly aims at increasing the wireless system throughput as well as improving the call-blocking ratios and end-to-end delays for real-time applications. This seamless communication enables both handling real-time multimedia traffics in a fair manner and granting call requests on the basis of the connection types. The system has been developed, modeled and simulated using OPNET Modeler. The simulation results show that the QoS-aware TDMA/FDD MAC with multi-beam DAs has substantially increased the system throughput and that the call-blocking ratio has been reduced from 86% to 18%, when the proposed MAC with 8-Beam antennas is employed instead of the regular MAC.

1. Introduction

Recently, the importance of wireless/mobile data communication has been increased, and the use of DAs has gained much importance to enhance the network capacity, together with the ever-increasing developments in both high performance wireless computers and QoS supported real-time multimedia applications. In addition, there has been a remarkable interest in developing new MAC (Medium Access Control) protocols for wireless networks equipped with smart antennas generally known as DAs to efficiently utilize the limited bandwidth.

Smart antennas (SAs) are one of the most promising technologies that enable a higher capacity in wireless networks by effectively reducing multi-path and co-channel interference. This is achieved by focusing the radiation pattern only in the desired direction. SAs employ a set of radiating elements arranged in the form of an array. The signals from these elements are combined to form a steerable or switchable beam pattern that follows the desired user/users. In a smart antenna system the arrays by themselves are not smart; it is the digital signal processing that makes them smart. The process of combining the signals and the focusing the radiation pattern in a particular direction is often referred to as digital beamforming [1,2].

The main goal of using DAs is to maximize the performance of the wireless networks by increasing capacity, range and Signal-to-Interference-Plus-Noise Ratio (SINR) and reducing end-to-end delay (latency). DAs provide an increased radiated power due to focusing the transmitter power on one and/or desired direction. This improves promptly the range of the transmitter. On the other hand, the directivity of the antenna allows the wireless station to cancel interfering signals arriving concurrently at the receiver from other directions [1–3]. Here the antennas work reciprocal, resulting in also increased power at the receiver.

Resource allocation and QoS management are of high importance in efficiently utilizing wireless system resources. Mainly focusing on the traffic at the MAC layer, several scheduling algorithms providing QoS supported communications have been researched actively [4–6]. However, the exploitation of the “space” is not capably considered in these works, resulting in not only worse call-blocking ratios but also not allowing the system to achieve higher throughputs. Concerning these shortcomings, many researchers have focused on deploying DAs in MACs [7–10]. Despite improving the performance of a slotted-ALOHA network with multiple beam adaptive arrays, QoS-aware communication was not concentrated in [7]. Similarly, [8] exploited the idea of SDMA; nevertheless, it did not have the projection to provide the multimedia applications of wireless terminals with the required level of QoS support. On the other hand, [9,10] presented two different approaches to maintain asymmetric traffics, however all ATM service classes (i.e., CBR, VBR, ABR and UBR) for broadband applications were not envisaged.

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doi:10.1016/j.csi.2008.09.035

In this work presented, a new QoS-aware MAC protocol based on TDMA/FDD (Multiple Access/Time Division Multiple Access/Frequency Division Duplexing), which allows QoS guarantees for multimedia application traffics (with ATM CBR, VBR, ABR and UBR service support) and utilizes DAs, has been designed, simulated and compared to a regular TDMA/FDD MAC counterpart utilizing omni-directional antennas. In the proposed MAC model, WTs (Wireless Terminals) use omni-directional antennas and communicate through a BS (Base Station) which is equipped with multi-beam DAs containing beamforming modules for both receiving and transmitting, each of which is capable of directing a beam at a predefined area in the space. The system model uses FDD for dublexing technique and employs a DSAT (Dynamic Slot Allocation Table) at the BS that is especially utilized for determining to which WT the slots will be assigned in the uplink (WT to BS) direction. By means of the DSAT in the BS, a new frame structure is constructed. This approach ensures an increased wireless system capacity, meanwhile reducing call blocking ratio and improving end-to-end delay performance with a multimedia traffic differentiating approach.

The paper is organized as follows. Section 2 presents a brief explanation of directional antenna systems and essentials of wireless ATM architecture facilitated especially for developing the new QoS algorithms. Section 3 points out previous researches on wireless MAC methods utilizing DAs. Overall properties and design stages of the proposed TDMA/FDD MAC protocol with related QoS algorithms and DAs are explained in detail in Section 4. Section 5 includes an example network scenario employing the proposed MAC technique, which has been modeled and simulated under varying and different type of traffic loads and increasing number of users, with OPNET Modeler including the Radio Module. The simulation results obtained from the new developed QoS-aware MAC models with different number of DAs are compared to those of their regular counterpart with omni-directional antennas under the same network conditions. And, the last section summarizes the proposed method with final remarks.

2. Preliminaries

2.1. Directional antenna systems

Recently, the need for providing high quality wireless access and the great demand on high speed wireless links have increased dramatically. Consequently, researchers have been motivated to enhance the wireless network capacity to meet the growing number of users and different types of application requirements. As a result, new sources have been focused on increasing the overall network performance. The use of DAs, especially designed to achieve the throughput expansions and to reduce the total communication delays as in the case of this work, is of much importance.

An omni-directional antenna is an antenna that radiates and receives equally well in all directions. Therefore, desired users are reached with only a small percentage of the overall energy sent out into the environment, leading to both waste of power and transmission in the directions where there are no terminals to reach. The use of omni-directional antennas directly and adversely affects the spectral efficiency and limits the frequency reuse [3,11,12].

DAs, when used appropriately in wireless communications, offer significant benefits in enhancing system performance by increasing channel capacity and spectrum efficiency. They reduce multi-path and increase range coverage as well. These antennas enable communication directionally by forming specific antenna-beam patterns [2,13]. The main beam, with increased gain, is directed to the desired user and/or a group of users while nulls are directed away from the main beam. In other words, electromagnetic waves are enhanced into certain directions while cancelled in others, resulting in an amplified signal directed to a certain area in space.

Implementation of DAs is basically described in two categories: switched beam systems and adaptive array systems [3]. The switched beam system has a switching mechanism enabling it to select and switch one of the predefined beams which provides the best directivity and gain to the selected region covering intended users. It does neither steer nor scan the beam in the direction of the desired signal. Switched beam systems can be divided into two groups: single beam and multi-beam DAs. In single beam DAs, only one beam is active at a given time. Simultaneous transmissions are not allowed because the system has only one transceiver. On the other hand, in multi-beam DAs, as utilized in this research work, there are several beam patterns and each of them is directed to a different area in the space. As the number of beams is equal to the number of transceivers, simultaneous transmissions are allowed at the same time and frequency. On the other hand, the adaptive array system tracks the mobile user continuously by steering the main beam towards the intended user and at the same time forming nulls in the other directions. It is out of the scope of the works carried out and presented in this paper, and therefore is not explained in detail.

2.2. QoS support in wireless ATM

The idea of quality of service support for real-time multimedia traffics has motivated researchers in wireless system development and implementation since the emergence of ATM. This key feature of the wireless ATM (WATM) architecture is well adapted to the proposed MAC presented in Section 4, where new QoS algorithms are incorporated with the benefits of using multi-beam DAs.

ATM requires bandwidth-rich media for its both classical and wireless applications. However, a wireless channel is a limited and extremely expensive resource. Thus the efficient use of this limited bandwidth is an indispensable part in WATM system development. Overcoming this drawback, WATM provides several significant advantages including; 1) flexible bandwidth allocation and service type selection for multimedia applications, 2) efficient multiplexing of bursty data and multimedia traffic sources, 3) a wireless platform with multimedia support for any QoS needs in a better way, 4) end-to-end provisioning of broadband services over wireless channels and 5) simple compliance with the requirements of wireless access to an ATM network [4,14].

Real-time multimedia applications cover up at least two media traffics (e.g., data, audio and video) to be transferred within certain and predefined QoS requirements. There are four well-known different service classes in ATM systems which have also inspired the development of new QoS algorithms utilized in the proposed MAC design, namely Constant Bit Rate (CBR), Variable Bit Rate (VBR), Available Bit Rate (ABR) and Unspecified Bit Rate (UBR).

Real-time digital audio and video applications require CBR and VBR-rt (real-time) service categories, respectively. For CBR services, the Peak Cell Rate (PCR) descriptor must be provided to the WATM network (called Peak Rate Allocation), while for VBR services, Minimum and Sustained Cell Rates (MCR and SCR) are also mandatory (called Dynamic Rate Allocation). Other QoS attributes (e.g., Cell Loss Ratio (CLR), Cell Delay Variation (CDV) and Cell Transfer Delay (CTD)) can be at a default setting within the ATM network. Interactive traffic and LAN interconnect traffic are carried over an ABR service. Applications using this service specify the MCR descriptor and can also add PCR, CDV, and CLR. Applications where guaranteed packet delivery is not required (e.g., Internet traffic and e-mail) are provided over a UBR service. Therefore, any cells sent on UBR connections have to wait until there is free bandwidth available and not being used by either CBR or VBR traffic [15–17].

WTs (Wireless Terminals) and BSs (Base Stations) can be fixed or mobile in WATM architecture. In the development phase of the proposed MAC, the networking environment is projected as including fixed (stationary) WTs and a BS, both with running parts of the new QoS algorithms concurrently.