UMTS–TDD: A Solution for Internetworking Bluetooth Piconets in Indoor Environments

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Abstract— **The last few years have seen the evolution of telecommunications from the classic architectures, mainly based on static and wired structures, to the new mobile solutions based on wireless technologies. This trend has led, on the one side, to the definition of the third–generation mobile telecommunication systems and, on the other, to the development of personal area networks. The standards that are supposed to play a leading role in these two fields in the near future are the Universal Mobile Telecommunication System (UMTS) and the Bluetooth (BT) radio technology, respectively. In this paper, we advocate that a hybrid architecture of UMTS and Bluetooth can take advantage of the complementary characteristics of these two technologies and provide a total solution for an indoor communication environment. We envision a cooperating scenario in which small Bluetooth networks (scatternets) offer basic wireless connectivity to several peripheral units scattered over small areas, while indoor UMTS supports communication among scatternets and provides wireless access to the Internet. We focus our analysis on a centralized topology, in which communication occurs only between the peripheral units and the access point. This topology can be used in many different application scenarios and represents an example of cooperation between 3G and PAN technologies. In addition to describing the architecture, we address the issue of fair capacity allocation in such a centralized topology and provide some analytic and simulation results for the topology considered.**

I. INTRODUCTION

The last few years have seen a revolution in the telecommunications world. There has also been a growing demand for a global network, which can allow people to connect anytime and anywhere. These trends have led, on the one side, to the definition of the third–generation mobile telecommunication systems and, on the other, to the development of personal area networks. The leading technologies in these two fields are the Universal Mobile Telecommunication System (UMTS) [1] and the Bluetooth (BT) [2] radio technology, respectively. While UMTS aims to provide "universal connectivity," which means the possibility of communicating from anywhere to anywhere, Bluetooth has been proposed to provide "ubiquitous connectivity," i.e., the possibility of communicating with (almost) every electronic device within short range.

Bluetooth is a short–range, low power, and low cost technology that is expected to be widely diffused in almost every electronic device in the future. Such a large diffusion may enable Bluetooth–enabled devices to be used in a wide array of applications in various network architectures. For instance, Bluetooth may provide wireless Internet Access in cafeterias, libraries, airports or, in general, in any environment in which this service is an added value offered to the customers, and low cost is more important than high performance.

However, the limited coverage range and the small number of users that can be arranged in a piconet represent severe constraints in realizing a pure–Bluetooth wireless network covering a wide area. The problem can be partially overcome by using scatternets to connect two or more piconets. Unfortunately, the performance offered by a scatternet rapidly degrades with the increasing of the scatternet size, while the complexity of maintaining and managing the structure increases. Consequently, some practical considerations limit the maximum extension of a scatternet.

The network may be extended beyond a scatternet by using other radio technologies with higher coverage range to connect scatternets. A possible solution may be based on the third generation cellular system technologies, and in particular on the unlicensed UMTS TDD [3] (Universal Mobile Telecommunication System, Time division Duplex) system, which has been specifically proposed to provide voice and data connection in indoor environments.

Each scatternet may contain a UMTS-Bluetooth hybrid unit and the UMTS TDD base station can be used to interconnect these hybrid–units in order to allow inter–scatternet communication. This leads to a hierarchical architecture, in which Bluetooth provides the basic wireless connectivity to the final users, while UMTS serves as a backbone, interconnecting several Bluetooth sub–networks. Such a solution can provide the low-cost service of Bluetooth and overcome its range limitations without much increase in the cost of the infrastructure. Moreover, the UMTS base station can allow network access to users equipped with a UMTS cellphone as well as private cordless communication among cellphones.

The hybrid solution may also be implemented by using other technologies such as 802.11 [4] in place of UMTS TDD. Though a solution based on 802.11 may provide a higher bandwidth, the current 802.11b has the problem of interference with Bluetooth [5]. In general, mobile users will typically have a Bluetooth or a UMTS interface and the proposed solution can support both these interfaces. An 802.11 interface may not be used in PDAs or other small devices due to its high power requirements. An 802.11 solution will not be able to support UMTS users. Furthermore, since UMTS is expected to be very widely deployed, one can imagine UMTS TDD base stations to be present in a lot of indoor environments. Hence, we base our hybrid architecture on UMTS TDD.

The rest of the paper is organized as follows. Section II describes the UMTS and Bluetooth technologies. A hybrid Bluetooth-UMTS architecture for indoor environments is proposed in Section III. Section IV deals with the management of the hybrid architecture and looks at the issue of fairness in such a system. Section V presents some simulation results of the proposed architecture and Section VI provides the conclusions.

II. TECHNICAL OVERVIEW

A. UMTS

UMTS is the third generation mobile communications system being developed within the IMT-2000 framework. UMTS will build on and extend the capability of today's mobile technologies (like digital cellular and cordless) by providing increased capacity, data capability and a far greater range of services.

There are mainly two air interface technologies for UMTS: UMTS–FDD and UMTS–TDD [3]. UMTS–FDD relies on wideband–CDMA (W–CDMA) technology and will be deployed in outdoor macro–cellular or micro–cellular communication environments. UMTS–TDD adopts a combination of CDMA and TDMA technologies and will be deployed in indoor pico–cellular communication environments. It allows asymmetric radio resource allocation between uplink and downlink and higher bit rates services than FDD and is expected to be used in indoor environments.

B. Bluetooth

Bluetooth [6] operates in the 2.4–GHz ISM (industrial, scientific and medical) band and uses a fast frequency–hopping technique to minimize interference. A Bluetooth unit has a range of approximately 10 meters. Two or more Bluetooth units sharing the same channel form a piconet. Each piconet consists of a master unit and up to seven active slave units. Furthermore, two or more piconets can be interconnected to form a scatternet. This requires a unit, called an inter–piconet unit (gateway), to be a part of more than one piconet.

III. AN INTEGRATED SCENARIO

In this section we consider a particular topology of systems that we refer to as "Centralized Wireless Local Area Networks" (CWLANs). These are systems in which data flows only between a central node, that we call a "concentrator node" (CN), and many wireless peripheral nodes (PN) scattered in a wide area.

Such a topology may be applied in many different scenarios. For instance, in an "Intelligent–Supermarket," a central server may contain information about each subscribed client - the usual grocery list, the kind of offers he may be interested in, his account information (credit card number), and so on. When the client enters the Supermarket, his identification code is sent to the server through a wireless network. The server can, then, send back different messages that may direct the client towards the products he is interested in, or advise him about "special offers." The messages may be displayed on the client's cell phone or palmtop or, perhaps, on a little screen applied to the market–cart.

Another possible application for the CWLAN topology may be a cafeteria, or a library, where wireless Internet access may be offered to customers through strategically–positioned Bluetooth base stations, which may be wirelessly connected to a single Internet Access Point.

Such an architecture can be provided by a combination of Bluetooth and UMTS, using a hierarchical approach, as shown in Fig. 1. At the lowest level of the hierarchy, Bluetooth base stations (masters), distributed strategically in a given area, provide wireless access to users in their cells (piconets). At the second level, such piconets can be connected to form a scatternet using Bluetooth gateway slaves appropriately placed. In each scatternet, data may be aggregated towards a Bluetooth/UMTS–hybrid unit, which serves as an interface between Bluetooth and UMTS. At the top level of the hierarchical structure, hybrid units connect to the UMTS TDD base station, which represents the CN of the whole system.

The hybrid unit has both the Bluetooth and the UMTS interfaces, which can work simultaneously. The routing layer of the hybrid unit decides which interface to send the incoming packet on.

We present a specific example of this general architecture in Fig. 2, which shows a scatternet at the second level of the hierarchy. The Bluetooth base stations are positioned such that there are no uncovered spots. The gateway units serve to connect the piconets into a scatternet. The hybrid unit is the master of the central piconet and other base stations connect to this hybrid unit through the gateways. In the figure, the gray lines connecting the hybrid unit to the other base stations show the multi–hop paths between them. Note that each gateway is shared by three piconets. The coverage area may be extended by using multiple such scatternets, which are connected to the UMTS TDD base station through their hybrid units.

Note that all users share the total capacity available at the CN, on the basis of the scheduling algorithm applied to the gateways. It would be desirable to give each slave an equal share of this capacity. However, users that are further away from the CN may be at a disadvantage with respect to those that are closer, since their paths to the CN may include a larger number of gateways. Moreover, a non–uniform distribution of users among piconets may lead to an unfair capacity allocation; piconets with a smaller number of users

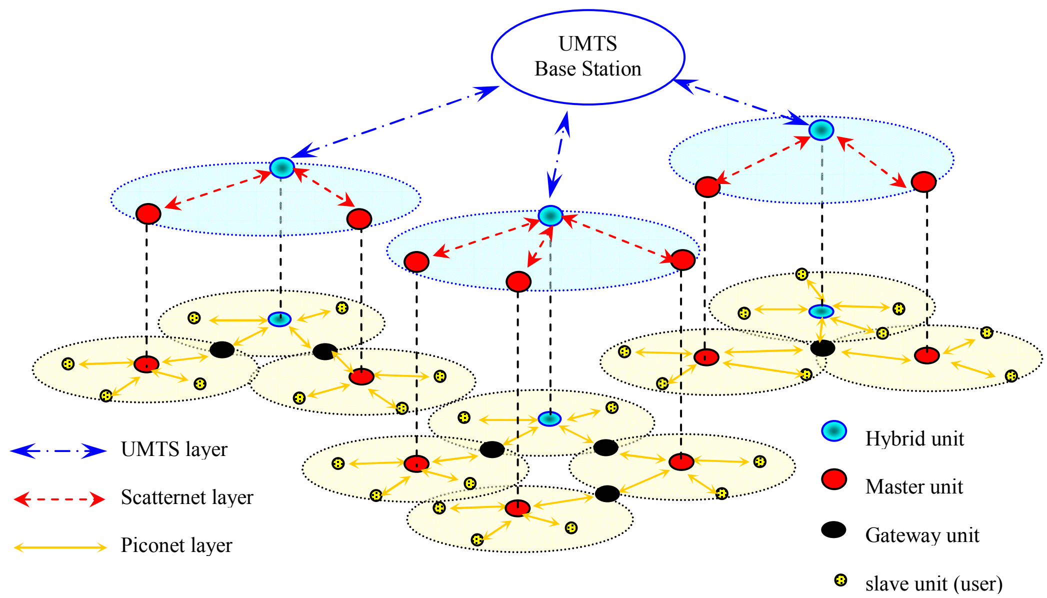

Fig. 1. "Centralized Wireless LAN Architecture" (CWLAN) using Bluetooth and UMTS

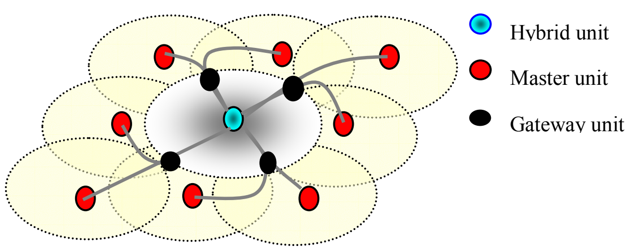

Fig. 2. An example topology of the architecture showing a 3x3 Bluetooth scatternet

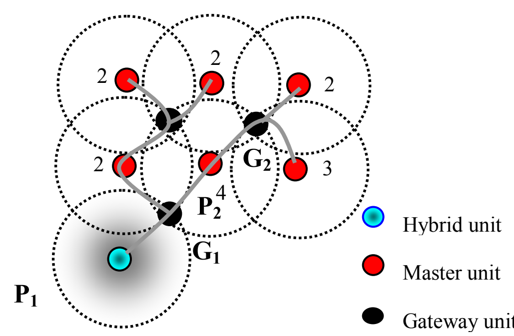

Fig. 3. Part of a scatternet showing the number of users (slaves) in the piconets

may provide higher capacity to their members than piconets with larger number of users. As we describe in the next section, a fair distribution of the bandwidth among the users may be achieved by a proper scheduling of the gateways.

IV. Scatternet Management

In the architecture introduced in Section III, the gateways act as forwarding units. Thus, a gateway must spend an equal amount of time in receiving data as in forwarding it. Since a gateway can be present only in one piconet at a time, the total capacity a gateway can provide to the users it serves[1] is bounded by half the piconet capacity. This prevents the distribution of the capacity in a fair manner when a gateway serves more than half the total number of users in the scatternet.

We now focus on a gateway of the central piconet. If this gateway serves a fraction f of the slaves, then it spends a fraction of time equal to the minimum of f and 0.5 in the central piconet. Thus, if f is greater than 0.5, the slaves served by the gateway get less than their fair share. As explained above, the total time spent by the gateway in the other two piconets it belongs to, should be equal to that spent in the central piconet. This time is distributed between these two piconets in a fair manner, depending upon the total number of users served by each of them, where the total number of users is the sum of the users in the piconet and those served by the other gateway in the piconet.

Fig. 3 shows an example of a part of a scatternet along with the number of users in some piconets. As before, the gray lines show the multi-hop paths between the hybrid unit and the other base stations. Note that piconets whose number of users is shown are served by the same gateway G_1 of the central piconet. Let the total number of users in the scatternet be 25 (only part of them are shown). Then, the gateway G_1 serves a fraction 15/25 of the total number of users and hence, spends a fraction 0.5 of its time in the central piconet. It divides its remaining time between the other two piconets,

[1] A user is served by a given gateway when its path to the CN includes that gateway.

giving each a forwarding fraction of 0.3 and 0.2 of its total time, respectively (since the piconets serve a total of 9 and 6 slaves respectively).

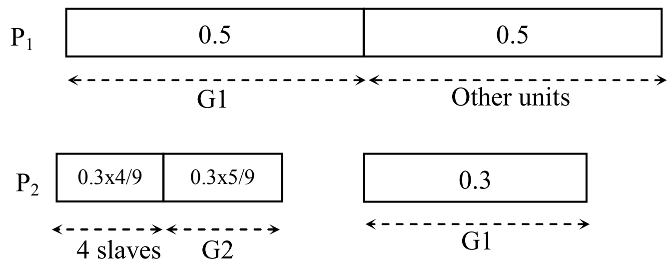

Fig. 4. Polling cycles of masters of P_1 and P_2

The forwarding fraction given to each piconet is now further divided in a fair manner. For example, the master of the piconet P2 divides the forwarding fraction giving a polling fraction of 0.3 to gateway G_1, 0.3*5/9 to gateway G_2 and 0.3*1/9 to each of the 4 slaves.

The system, thus, divides its bandwidth among the slaves as fairly as possible. In particular, if the number of slaves in the piconets is distributed in a uniform manner (i.e., the number of slaves served by one gateway is not greater than half of the total number of slaves), the system gives each slave an equal amount of bandwidth towards the hybrid unit.

This fair division requires a coordination of gateways and masters that may be implemented as shown by the polling cycles of masters of piconets P_1 and P_2 in Fig. 4. The length of the polling cycle is the same for all masters. Note that the master of piconet P_2 does not need to poll any unit for some time, which it may use for other activities (e.g. power saving). The gateway G_2 may also enter a power-save mode during the time it is not scheduled in any piconet.

If there is a change in the number of slaves in any piconet, the master of the piconet communicates it to the master of the central piconet, which reorganizes its polling cycle. This may lead to a reorganization of the polling cycles of other masters too.

The UMTS base station uses a dynamic radio resource allocation algorithm [7], where bandwidth is allocated to individual mobile terminals on the basis of their queue lengths. This can give a more efficient allocation of the UMTS channel among the hybrid units when they offer different amounts of traffic. However, if the total traffic offered to the UMTS base station exceeds the channel capacity, a hybrid unit offering higher traffic may get more than its fair share of the channel capacity. Thus, the algorithm may not guarantee fairness in such a situation.

V. Simulation Model & Results

In this section we first describe the simulation model used and then present simulation results of the proposed architecture.

A. Simulation Model

We used GloMoSim [8], a scalable simulation library, to develop both the Bluetooth and the UMTS models. These simulation models were then integrated into a hybrid UMTS–Bluetooth model.

The Bluetooth simulator implements the baseband and L2CAP layers according to the specifications [6]. In the experiments, the connection type used is ACL (Asynchronous Connectionless).

The UMTS simulator was developed according to the specifications [1]. In the simulations, we adopt turbo coding with 1/3 forward error correction (FEC) and the selective reject scheme for error control. A dynamic radio resource allocation algorithm [7] is used, as explained earlier.

The Bluetooth–UMTS hybrid model integrates both the Bluetooth and UMTS models for a comprehensive indoor communication environment. Each hybrid unit has both the Bluetooth and the UMTS interfaces and its routing layer forwards a packet on the appropriate interface.

B. Results

In the experiments, the routing protocol used is AODV [9] and each experiment is run for 2 minutes.

In the first experiment, we consider a scenario where an area of approximately 40x40 square meters is covered by a 9 piconets cell as shown in Fig. 2. Let P_{ij} denote the piconet at row *i* and column *j*. The hybrid unit is the master of the piconet P_{22} and connects to the UMTS TDD access point. The users are distributed such that the number of slaves in P_{11} varies from 1 to 6, P_{21} has 3 slaves and all other piconets have 1 slave each. Each user has a TCP connection with the UMTS base station.

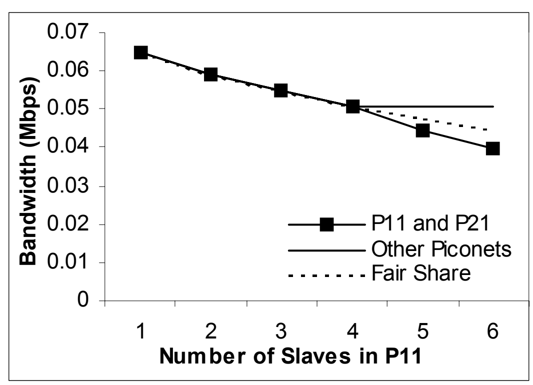

Fig. 5. Bandwidth obtained by TCP connections

Fig. 5 shows the bandwidth obtained by a TCP connection in each piconet. When the number of slaves in P_{11} is less than or equal to 4, all slaves get a fair share of the bandwidth. When the number of slaves in P_{11} becomes greater than 4, the gateway of the central piconet, which serves P_{11} and P_{21}, serves more than half of the total number of slaves. Thus, we see in the figure that users of P_{11} and P_{21} obtain less than their fair share while other users obtain more than their fair share,.

In the next experiment, we consider three Bluetooth scatternets, each one having the same topology as shown in

Fig 2. In each scatternet, piconets P_{11}, P_{13}, P_{31} and P_{33} have one user each, while the other piconets are empty. The hybrid unit in each scatternet connects to the UMTS TDD base station. Each user performs file transfers with the UMTS base station using TCP connections. The users of scatternet I generate files of 100 Kb and the time between the generation of two files is uniformly randomly distributed with a mean of 4 sec. Thus, scatternet I generates a total traffic of 100 Kbps (each user generates 25 Kbps). The traffic parameters for scatternet II are file size = 100 Kb, mean time between files = 0.8 sec and total traffic = 500Kbps. The traffic parameters for scatternet III are file size = 100 Kb, mean time between files = 0.57 sec and total traffic = 700Kbps.

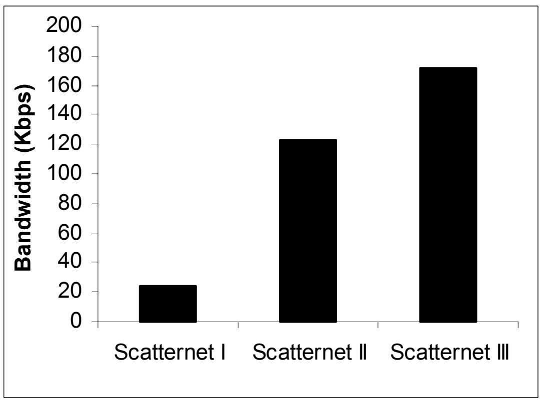

Fig. 6. Bandwidth obtained by each TCP connection of the three scatternets

Fig. 6 shows the bandwidth obtained by a TCP connection of the three scatternets (each TCP connection of a particular scatternet obtains the same bandwidth). It can be seen that this bandwidth is proportional to the traffic offered, due to the dynamic resource allocation algorithm used by the UMTS base station. On the contrary, a static allocation would not be adaptive to different traffic and would lead to an inefficient utilization of the UMTS bandwidth.

VI. Conclusions

In this paper, we presented a hybrid architecture of UMTS and Bluetooth that can provide a solution for wireless access in an indoor environment. Such a solution has the low-cost advantage of Bluetooth without the limitations of its small range. We discussed some of the advantages of using a UMTS TDD system in this solution. We also presented a specific topology example of the hybrid architecture and addressed the issue of fairness among users through analysis and simulations. The results show that this architecture can provide fairness among the users in a scatternet as long as they are not highly concentrated in one section. Moreover, the dynamic resource allocation algorithm implemented at the UMTS base station can achieve an efficient utilization of the bandwidth.

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