A Framework Architecture Supporting QoS-Power Trade-offs for Heterogeneous Network Systems

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Abstract

Power awareness and Quality of Service (QoS) integration in wireless systems are two of the main research activities in wireless systems today. As frameworks are developed to handle dynamic reconfiguration, the need for a power optimization methodology to investigate alternative cross-layer configurations is imposed as critical. However, as networks become more complex and energy savings become critical, this leads to the consideration of constructs for treating QoS-power trade-offs and adjust to the heterogeneous nature of network systems. In this paper, we propose an interoperable architecture for a hybrid wired-wireless network, where communication is treated transparently and enhancements are proposed to improve QoS by the definition of a framework also supporting dynamic power optimization.

1. Introduction

The need for interoperability of heterogeneous wired/wireless networks stems from the requirement for integrating the communication constructs in advanced industrial control applications. As the complexity degree of these applications increases over the years, miscellaneous network traffic must be curried through different mediums in a macroscopically homogeneous way. An interoperable architecture is thus required for a hybrid 802.11 [1] and Ethernet [2] network system, where communication is treated transparently to the higher-levels. Designing such an architecture is a complex task since two very different network architectures must interoperate. On one hand, there is a very well known network such is the wired Ethernet tested in all sort of application environments and able to cope with high time constrained demands. On the other hand, the relatively new ad hoc networks, which although has attracted a great deal of research interest in the resent years still lack in all performance parameters compared with the wired Ethernet networks [3].

In any case, it is critical that from the user point of view the whole system is seen as a black box and is expected to function equally well independently from its heterogeneity concerning the wired and wireless parts that comprise it. Consequently, the introduction of new constructs is required along with novel protocols in MAC and Network layers, which will diminish the deficiencies of the wireless part so as to cooperate smoothly with the wired counterpart. Besides dealing with heterogeneity, the innovative protocols for the wireless part tend to consider QoS parameters in order to improve network performance. However, the mobile nature of network systems under study imposes an imperative requirement for the network node life-cycle extension in terms of power consumption minimization. Power-awareness involves also higher-level parameters and thus a cross-layer middleware is required to handle power aspects in distributed networks of high heterogeneity.

In this paper, an interoperable middleware architecture is proposed, handling network heterogeneity and QoS tenability. Also a great benefit from the development of this framework is to study the trade-offs that exist between critical network parameters like QoS and power consumption so as to find the optimal balance between them especially as far as power aware interoperable networks are concerned. Additionally, application layer is also involved in this cross-layer study of the wireless network stack with respect to its impact on network communication and its performance concerning network parameters like delay, throughput and power consumption. In section 2, related work is discussed and in section 3 the middleware architecture and optimization objectives are presented. The network and MAC layer QoS-related enhancements are defined in section 4 and the case study application is described in section 5.

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2. Related work

Integration of QoS awareness in wireless networks is a growing research area, as timeliness and application-related constraints must be addressed by the network components. Dynamic variation of CPU parameters like frequency and voltage takes into consideration demands from OS services and application QoS demands through a flexible framework [4]. An adaptive Point Coordination Function (PCF) algorithm is presented in [5], based on recent polling feedback. The point coordinator uses an AIMD algorithm in order to maintain an active polling list. This architecture results to better medium utilisation and successful poll rate.

Several prototype frameworks have been developed to integrate QoS in the different system layers, ranging from improvements in UDP, TCP performance [6] to the exploitation of the spatial reuse advantage using directional antennas [7][8]. This idea is accompanied by a dedicated MAC and routing protocol. Although the documentation is very detailed and the results very promising, it was not followed by contemporary research. It must be pointed out however that controlling such antennas needs high precision and it’s highly energy consuming.

Considering power optimization in the context of wireless network communication, frameworks must be considered with respect to cross-layer architectures, as tight interdependencies exist among the different layers. In [9] a new routing protocol is proposed using information from the MAC layer protocol with sole purpose to reduce power consumption. Energy Constrained Path Selection (ECPS) assigns a value at each feasible route and the route with the highest value is selected, while Energy Efficient Load Assignment (E2LA) considers a certain number of possible routes and studies how packets can be distributed among these routes to achieve highest power conservation. In [10] an on/off scheduling is presented based on the close cooperation of MAC and routing protocol. It demands rigorous synchronisation, the presence of a base station as well as specific applications. However, under certain conditions performs well concerning power but not affecting the timeliness of the network. A MAC-physical layer cooperation is described in [11], where RTS-CTS control packets are used as information carriers for the congestion level of the channel. This information is used to control the transmission rate by dynamically varying the size of the digital constellation. New metrics are inserted in the routing protocol but the effect of these changes on power consumption is not addressed.

3. Framework architecture

As shown in Fig. 1, the core component of the proposed optimization framework is the Tunnelling Manager, which is responsible for monitoring the system, coordinating the system functional components by determining the optimal configuration scenario that minimize power with respect to traffic performance parameters. The optimal scenario is generated based on predefined action rules, which investigate alternative configurations for improved performance.

The proposed framework follows the common understanding that any decision support system must include the following behavioural categories: information acquisition, information processing and decision delivery. Thus the principal functions are to:

- Configure the parameters of the application and communication layers at run-time.
- Manage the parameters of the network components at run-time.
- Ensure the normal operation of the system.
- Provide optimal control set points for the network functional parameters with respect to power and reliability.
- Process historical data on the performance of the overall system in order to assess reliable QoS.

The Tunnelling Manager applies optimization techniques to handle trade-offs among the parameters that are advertised by the system sub-layers through the Middleware Interface. Based on action rules and the Management Information Base (MIB), the optimal configuration is set across all layers.
3.1. Optimization objectives

The proposed framework architecture deals with the performance optimization in terms of power consumption, QoS and time constraints. Since wireless networks are widely used as a solution to every kind of critical situation, timeliness has become one of the most important and complex goals involved in network designs. Moreover, they must be able to satisfy not only best-effort traffic but both soft and hard real time traffic as well. This task is even more complex, when heterogeneous networks are considered as holds also in the proposed case study. In order to guarantee such behavior, great attention must be paid to the maximum delay and the distribution of delays observed in the network, so as to see how well soft and hard real time constrains are met. However, different applications have different demands on bandwidth, delay, throughput and other network parameters. Consequently, it is imperative to support multiple QoS requirements as all kinds of traffic may be transmitted simultaneously.

Last but not least, power consumption is an important aspect of wireless networks, where nodes operate on non-renewable power source. Contemporary routing protocols focus mainly on finding the shortest route in terms of hop count. This concept is not adequate for ad hoc networks leading to excessively burdening of certain nodes with receiving/forwarding packets and consequently to early energy depletion of those nodes, which causes the early loss of optimal route, the need for frequent rediscovery of new routes, network partition and other network deficiencies. The main goal of the proposed framework is to improve these deficiencies, with a more sophisticated routing discovery, involving new criteria in order to increase the node lifetime and conclusively the whole network lifetime. Furthermore, through these algorithms the mean delay and throughput is considerably improved.

Some parts of the above work have been standardised and it is already followed by many commercial implementations. Hence, the proposed framework must be compatible with all popular wireless stack layer protocols in order to observe and direct compare all network parameters improvement.

3.2. Middleware Interface

A middleware interface is defined at every layer to manage configuration parameters. As shown in the UML diagram of Fig. 2, a generic middleware interface is used by the Tunnelling Manager to manage the states of the system sub-layers through the start, stop and sleep functions respectively.

Through the GetStatus function the Tunnelling Manager has the ability to monitor the current status of every sub-layer functional component, while by the SetConfiguration function the optimal parameter values are passed to the target sub-layer module. The generic UML middleware interface is suited to handle the heterogeneous nature of the case study system architecture, where both wired and wireless sub-networks are interconnected and thus, the proposed framework should be able to tunnel both.

3.3. Cross-layer optimization technique

Cross-layer design aims at treating the different layers considering their interdependencies and not in isolation. Therefore, each specific layer is considered in conjunction with others, with which strong interaction exist and can be exploited in order to improve the whole network performance. Indicative motivations that lead to the need for cross-layer design are the fact that optimization can be achieved in multiple layers like power conservation and that optimization in one layer may need cooperation with other layers to show its effects. However, as conflicts exist between optimization goals and some situations do not need support by all layers, trade-offs must be handled and several optimisation alternatives must be considered. Many examples exist showing the interplay between layers and network parameters advocating the use of cross-layer technique [12][13][14].

The main focus of this work is on the interaction between Network and MAC layers. Contemporary routing algorithms use mainly as metric the minimum hop route, burdening continuously the same nodes,

![Figure 2. Middleware interface UML model](image-url)
leading to congestion increase in the vicinity of these nodes and early energy depletion with many negative consequences. Moreover, when multiple data flows exist having a routing protocol not concerned with the possible conjunction of these flows affects the MAC layer leading once more to congestion and consequently delays increase. Besides, designing more computational intensive and complex protocols, a middleware is proposed for supporting the cooperation between Network and MAC layers. Network performance is improved by the definition of a “usage factor” depending upon the remaining power of a node, the QoS and the application’s priority demands. Every node “advertises” its remaining power without adding communicational overhead i.e. by using routing packets and not transmitting new ones. In this way, the middleware obtains a clear view of the remaining nodes power and decides whether the route suggested by the routing protocol is optimal, in terms of network and node lifetime. Moreover, this information is used to avoid network partition for as long as possible and at the same time satisfy the application QoS in the best possible way. If there is strong possibility to have a more favourable route than that proposed one by the routing protocol the middleware will generate a new route. In certain cases, where the protocol sustains multiple routes like in Dynamic Source Routing (DSR), the framework can actively participate in the selection of the optimal route.

The efficiency of TCP protocol usage in wireless networks is also studied, as modifications are required in order to distinguish loss attributed to congestion and losses due to the nature of wireless transmission medium. As treating both cases in the same way has proven to have a negative performance influence, a distinction must be made at MAC layer, where network performance can benefit from the cooperation of these two layers.

4. Performance optimization in wireless protocol stack

Performance optimization in wireless networks is related to throughput maximization, fair bandwidth usage, load balancing and guaranty of end-to-end timeliness. Based on the wireless protocol stack, the basic functionalities are defined and optimized in terms of integrated QoS awareness.

4.1. Network layer

The network layer in wireless networks is responsible to find and maintain routes to some or all other nodes in the wireless domain, through the use of a routing protocol. This simply means that each node in the wireless network also plays the role of a router, and must be able to forward packets that are not destined to it but to the final destination.

Routing protocols are divided in to three general categories, namely proactive, reactive and hybrid. This categorization is based on the way each protocol is trying to establish and maintain routes to all stations in the wireless domain. Proactive is any protocol that maintains routes to all nodes in the domain, by using functions that periodically discover routes. The periodic nature of these protocols is the main reason that they have higher bandwidth overhead, and lower route acquisition times. On the other hand reactive protocols, such as DSR, are initiating route acquisition procedures only when a packet is in the nodes’ queue to be sent to some destination node. This imposes some delay in the packet due to higher route acquisition time. On the other hand, it reduces the overall network bandwidth overhead in case of low network traffic, where routes are found only for the destination nodes of the packets to be sent and not for the whole domain. Hybrid routing protocols such as Zone Routing Protocol (ZRP) use both of the above techniques to establish and maintain routes to destination nodes.

Many routing protocols for wireless networks have been introduced and tested, the most known and promising being DSR [15] and AODV [16] of the reactive family, proactive OLSR [17] and finally ZRP [18], a hybrid protocol introducing a framework that uses both proactive and reactive functions to establish and maintain routes. The above protocols cover the whole area of routing protocols. These protocols can be optimized based on the nature of the protocol:

- Proactive protocols can accept dynamic configuration of their update interval between network topology discovery.
- Reactive networks can be configured to make flooding of discover packets more intelligent with the use of hop limited searches instead of flooding the entire network with route request packets.
- Hybrid network protocols like ZRP are more open to optimizations and dynamic configurations since they bind together the two above families of protocols and so all their configurable parameters. Furthermore ZRP introduces new parameters that are fully configurable and can have a major impact in network efficiency

Based on ZRP, an adaptive routing protocol is incorporated in the proposed framework [19]. The adaptive zone routing protocol (AZRP) takes into account the current state of the network in the vicinity of the node and configures dynamically each node’s: i) zone radius attribute of ZRP, ii) interval between consecutive updates of intra-zone routing protocol (IARP). AZRP adapts to network states of low and high
traffic resulting in optimal power consumption. More precisely, through the use of a low zone radius, transmission of any unnecessary route discovery packets is avoided in low network traffic-mobility state. In the opposite case of high network traffic and mobility, a wider zone radius results to lower end-to-end delay.

4.2. Data link layer

The IEEE 802.11 MAC architecture is shown in Fig.3. The MAC sub-layer defines two access coordination mechanisms, the basic Distributed Coordination Function (DCF), which is mandatory and the optional Point Coordination Function (PCF). Networks that are making use of both DCF and PCF functions support two kinds of transmissions: asynchronous and synchronous.

Asynchronous transmission is provided by DCF, which is basically a CSMA/CA access method, while synchronous transmission provided by PCF follows a round-robin polling-based access mechanism. The most important features when dealing with a wireless MAC protocol is channel access and QoS maintenance in terms of throughput, delay etc. The DCF mechanism can only support best-effort services. Hence, no QoS guarantees are provided for typically time-bounded services such as voice. On the other hand, PCF supports time-bounded applications and generally provides QoS characteristics.

5. Case study

The proposed framework and protocol optimizations are driven by the need of transparent multimedia traffic over heterogeneous wireless-wired networks, where end-to-end time constraints must be met and the need for maximizing the system-wide life-cycle is more than imperative. The case study of the proposed framework, shown in Fig. 4, consists of audio streams transfer over a hybrid wireless-wired network topology.

The analysis and testing of the audio application over the hybrid network architecture reveals the following bottlenecks that are treated by the proposed framework:

i. Audio streams transfer over the wireless medium with the enhanced routing and MAC protocols to provide high throughput and low packet loss.

ii. Audio streams transparent transfer over the wired-wireless connection through the interoperable device architecture.

iii. Trade-off handling between application layer constraints and network layer performance.

iv. Trade-off handling between application layer constraints and MAC layer performance.

v. Power savings with respect to optimal QoS.

5.1. Network system architecture

The network architecture consists of two physical media, one wired and one over the air. The hybrid topology corresponds to the wireless 802.11-based part and to the wired Ethernet-based protocol. In order for multimedia traffic to be carried through transparently over the two media, the wireless node wn8 must transfer the audio packet from the wireless network part (wn2/wn5) to the wired Ethernet part (en4/en1) under end-to-end time and quality constraints. As holds for all multimedia applications also for audio applications, the user perceptive quality defines tight QoS requirements that the hybrid network should support. More precisely, wn8 keeps a map of all network nodes status in order to be able to serve a future request, while meeting a user acceptable QoS with respect to non-interrupted audio stream delivery for rendering.

Figure 3. IEEE 802.11 MAC Architecture

Even though PCF was initially developed for QoS applications, this mode of operation suffers some severe problems, leading to poor QoS characteristics. For example both simple round-robin polling algorithm and the static nature of the DCF-PCF switching, provided by the standard, are questionable. A dynamic polling algorithm based on scheduling as well as a fairer DCF-PCF switching would enhance the poor QoS performances, provided by the standard, leading to higher throughput and less delays. In [20], an architecture of a novel medium access control MAC algorithm is discussed, using a slotted point coordination function called S-PCF. The provided diagrams show that this new scheme can enhance the QoS of multimedia traffic in 802.11 WLAN. All the above algorithm’s enhancements can be applied and implemented within an Access Point (AP) and be fully compatible with the IEEE 802.11 standard.
Apart from inter-network QoS consideration, the proposed enhancements for routing and scheduling algorithms in the wireless network nodes at network and MAC layer respectively, render the wireless network QoS-aware and as such related parameters are treated by the framework for QoS versus power optimization.

6. Conclusions

The architecture for a power optimization framework is presented to cover the needs of holistic integrated network control. The basic constructs have been defined to support the framework in treating performance related parameters in a cross-layer basis and integrating them into a power optimization problem, whose ultimate objective is to generate an optimal reconfiguration of the cross-layer modules. Besides optimization and run-time monitoring, the network system architecture is analyzed in order to make the hybrid wireless-wired connection transparent and interoperable.

Finally, enhancements are studied for the network and data link layers to integrate QoS parameters in the wireless network and thus, increase the freedom degree for the framework to apply power optimization. The appropriate interfaces have been defined through the use of formal description models.

The framework architecture allows for future integration of additional modules, should more impact factors of other layers be required. The system design is flexible and the UML model open and adaptable for extension to cover applications of different multimedia particularities or even fulfill the need of multi-dimensional trade-off solving.

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