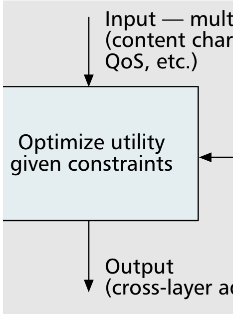
CROSS-LAYER WIRELESS MULTIMEDIA TRANSMISSION: CHALLENGES, PRINCIPLES, AND NEW PARADIGMS

MIHAELA VAN DER SCHAAR, UNIVERSITY OF CALIFORNIA, DAVIS
SAI SHANKAR N, QUALCOMM INC., USA[1]



> As the use of wireless local area networks spreads beyond simple data transfer to bandwidth-intense, delay-sensitive and loss tolerant multimedia applications, addressing Quality of Service (QoS) issues will become extremely important.

ABSTRACT

Wireless networks are poised to enable a variety of existing and emerging multimedia streaming applications. As the use of wireless local area networks spreads beyond simple data transfer to bandwidth-intense, delay-sensitive, and loss-tolerant multimedia applications, addressing quality of service issues will become extremely important. Currently, a multitude of protection and adaptation strategies exists in the different layers of the open systems interconnection (OSI) stack. Hence, an in-depth understanding and comparative evaluation of these strategies are necessary to effectively assess and enable the possible trade-offs in multimedia quality, power consumption, implementation complexity, and spectrum utilization that are provided by the various OSI layers. This further opens the question of cross-layer optimization and its effectiveness in providing an improved solution with respect to the above trade-offs. In this article we formalize the cross-layer problem, discuss its challenges, and present several possible solutions. Moreover, we also discuss the impact the cross-layer optimization strategy deployed at one station has on the multimedia performance of other stations. We introduce a new fairness concept for wireless multimedia systems that employs different cross-layer strategies, and show its advantages when compared to existing resource allocation mechanisms used in wireline communications. Finally, we propose a new paradigm for wireless communications based on coopetition, which allows wireless stations to harvest additional resources or free up resources as well as optimally and dynamically adapt their cross-layer transmission strategies to improve multimedia quality and/or power consumption.

INTRODUCTION

Due to their flexible and low cost infrastructure, wireless local area netwoks (LANs) are poised to enable a variety of delay-sensitive multimedia applications, such as videoconferencing, emergency services, surveillance, telemedicine, remote teaching and training, augmented reality, and entertainment. However, existing wireless networks provide only limited, time-varying quality of service (QoS) for *delay-sensitive*, *bandwidth-intense*, and *loss-tolerant multimedia applications*.

Fortunately, multimedia applications can cope with a certain amount of packet losses depending on the sequence characteristics and error concealment strategies available at the receiver. Consequently, unlike file transfers, real-time multimedia applications do not require complete insulation from packet losses, but rather that the application layer *cooperate* with the lower layers to select the optimal wireless transmission strategy that maximizes multimedia performance.

NEED FOR CROSS-LAYER OPTIMIZATION

In recent years the research focus has been to adapt existing algorithms and protocols for multimedia compression and transmission to the rapidly varying and often scarce resources of wireless networks. However, these solutions often do not provide adequate support for multimedia applications in crowded wireless networks, when interference is high or stations are mobile. This is because the resource management, adaptation, and protection strategies available in the lower layers of the stack — the physical (PHY), medium access control (MAC), and network/transport layers — are optimized without *explicitly* considering the specific characteristics of multimedia applications, and conversely, multimedia compression and streaming algorithms do not consider the mechanisms provided by the lower layers for error protection, scheduling, resource management, and so on. This "layered" optimization leads to a simple independent implementation, but results in suboptimal multimedia (objective and/or perceptual quality) performance. Alternatively, under adverse conditions, wireless stations need to optimally adapt their multimedia compression and transmission strategies jointly across the

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protocol stack in order to guarantee a predetermined quality at the receiver.

In this article we present a cross-layer framework for *jointly* analyzing, selecting, and adapting the different strategies available at the various OSI layers in terms of multimedia quality, consumed power, and spectrum utilization. Developing such an integrated cross-layer framework is of fundamental importance, since it not only leads to improved multimedia performance over existing wireless networks, but also provides valuable insights into the design of next-generation algorithms and protocols for wireless multimedia systems. The proposed cross-layer approach does not necessarily require a redesign of existing protocols [1], and can be performed by selecting and jointly optimizing the application layer and the strategies available at the lower layers, such as admission control, resource management, scheduling, error protection, and power control.

Article Outline

The article is organized as follows. The existing research on multimedia adaptation and protection for wireless transmission is briefly reviewed. We formalize the cross-layer design problem and discuss the challenges associated with solving this problem. We present several illustrative examples of how cross-layer optimization can be performed, and its impact on multimedia quality and power consumption. We then discuss how the cross-layer strategy deployed at one station impacts the performance of competing stations as well as system-wide utilization of resources. We also propose a new paradigm for cross-layer optimization and resource management for multimedia transmission. The conclusions are then outlined.

Brief Review of Adaptation and Protection Strategies at Different Layers

Numerous solutions have been proposed for efficient multimedia streaming over wireless networks. Potential solutions for robust wireless multimedia transmission over error-prone networks include application-layer packetization, (rate-distortion optimized) scheduling, joint source-channel coding, error resilience, and error concealment mechanisms [2]. An excellent review of channel-adaptive multimedia streaming research is provided in [3].

Transport issues for wireless (multimedia) transmission have been examined in [4]. At the PHY and MAC layers, significant gains have been reported by adopting cross-layer optimization, such as link adaptation, channel-aware scheduling, and optimal power control [5]. However, these contributions are aimed at improving throughput or reducing power consumption without taking into consideration multimedia content and traffic characteristics. Explicit consideration of multimedia characteristics and requirements can further enhance the important advances achieved in cross-layer design at the lower layers. Possible solutions and architectures for cross-layer optimized multimedia transmission have been proposed in [6–8].

To provide QoS for multimedia applications, the IEEE 802.11 Working Group has currently defined a new supplement to the existing legacy 802.11 MAC sublayer, called IEEE 802.11e [9]. Note that even though emerging MAC standards provide QoS support, there are no QoS guarantees for multimedia applications, and system-wide resource management is not always fair or efficient. This is due to the time-varying nature of the wireless channel and multimedia characteristics, and also the lack of cross-layer awareness of the application and MAC layers about each other.

Note that even though emerging MAC standards provide QoS support, there are no QoS guarantees for multimedia applications and system-wide resource management is not always fair or efficient.

The Cross-Layer Design Problem

We formulate the cross-layer design problem as an optimization with the objective to select a joint strategy across multiple OSI layers. In this article we limit our discussion to PHY, MAC, and application (APP) layers since we consider only one-hop wireless networks. In these networks the network layer plays a less important role, and multimedia streaming uses Real-Time Transport Protocol (RTP) and User Datagram Protocol (UDP), so the transport layer is less important for error protection and bandwidth adaptation. Nevertheless, the proposed framework can easily be extended to include other layers. Let N_P, N_M, and N_A denote the number of adaptation and protection strategies available at the PHY, MAC, and APP layers, respectively. For instance, the strategies PHY_i, $i \in \{1, 2, \dots N_P\}$, may represent the various modulation and channel coding schemes existing for a particular WLAN standard. The strategies MAC_i, $i \in \{1, 2, \dots N_M\}$, correspond to different packetization, automatic repeat request (ARQ), scheduling, admission control, and forward error correction (FEC) mechanisms. The strategies App_i, $i \in \{1, 2, \dots N_A\}$, may include adaptation of video compression parameters (including enabling spatiotemporal signal-to-noise ratio [SNR] trade-offs), packetization, traffic shaping, traffic prioritization, scheduling, ARQ, and FEC mechanisms. We define the joint cross-layer strategy S as

$$S = \{PHY_1, \dots, PHY_{N_P}, MAC_1, \dots MAC_{N_M}, \dots\}. \quad (1)$$

It is clear from Eq. 1 that there are $N = N_P \times N_M \times N_A$ possible joint design strategies. The cross-layer optimization problem seeks to find the optimal composite strategy represented by the following equation:

$$S^{opt}(\mathbf{x}) = \arg\max_{S} Q(S(\mathbf{x})). \quad (2)$$

This strategy results in the best (perceived/objective) multimedia quality Q subject to the following wireless station constraints:

$$\begin{aligned} &Delay\ (S(\mathbf{x})) \le D_{\max}, \\ &Power\ (S(\mathbf{x})) \le Power_{\max}, \end{aligned} \quad (3)$$

as well as overall system constraints, such as fairness strategies and bandwidth allocation. Given the instantaneous channel condition $\mathbf{x} = (SNR, contention)$, maximum tolerable delay $D_{\max}$, and maximum power $Power_{\max}$, we need to solve Eq.

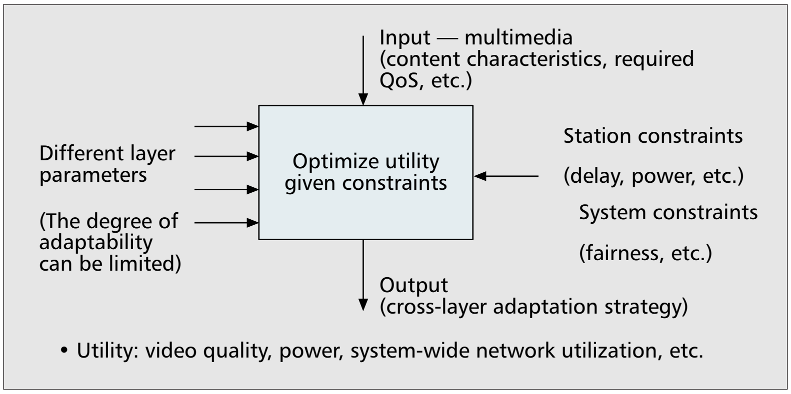

Figure 1. *The conceptual framework of cross-layer optimization.*

2 subject to the wireless station and system constraints.

Figure 1 shows the conceptual scheme of the proposed cross-layer optimization framework.

Finding the optimal solution to the above cross-layer optimization problem is difficult because:

- Deriving analytical expressions for Q, Delay, and Power as functions of channel conditions is very challenging, since these functions are nondeterministic (only worst case or average values can be determined) and nonlinear, and there are dependencies between some of the strategies PHY_i, MAC_i, APP_i (see Example 1 below).
- The algorithms and protocols at the various layers are often designed to optimize each layer independently and often have different objectives. Moreover, various layers operate on different units of multimedia traffic and take as input different types of information. For instance, the physical layer is concerned with symbols and depends heavily on the channel characteristics, while the application layer is concerned with semantics and dependencies between flows, and depends heavily on the multimedia content.
- The wireless channel conditions and multimedia content characteristics may change continuously, requiring constant updating of parameters.
- Formal procedures are required to establish optimal *initialization*, *grouping* of strategies at different stages (i.e., which strategies should be optimized jointly), and *ordering* (i.e., which strategies should be optimized first) for performing the cross-layer adaptation and optimization.
- Finally, different practical considerations (e.g., buffer sizes, ability to change retry limits or modulation strategies at the packet level) for the deployed wireless standard (e.g., 802.11e QoS MAC supports unequal error protection for different flows or delay awareness, unlike traditional 802.11a/b/g MAC) must be taken into account to perform the cross-layer optimization.

Fortunately, the number of protection and adaptation strategies at the various layers is relatively small (e.g., only eight modulation strategies can be selected at the physical layer for the 802.11a wireless standard), thereby reducing the space of possible solutions. We present an example based on our research in [10] to highlight the dependencies among these strategies.

Example 1. Figure 2 shows the dependency of the optimal[2] application-layer packet sizes L_a^* on the MAC retry limit R (=0, 1, 2), given that a (63,49) Reed-Solomon code was deployed at the APP layer and a modulation strategy $m = 5$ was used at the PHY layer (see [10] for details). It can be seen that as SNR improves, the optimal packet size should be increased. However, the rate at which the APP packet size increases for different SNRs depends on R.

OPTIMIZATION METHODS FOR CROSS-LAYER DESIGN

In this section we discuss the challenges in solving the cross-layer optimization problem, identify various classes of solutions, and illustrate how the cross-layer optimization can be performed using several examples.

CHALLENGES IN SOLVING THE CROSS-LAYER OPTIMIZATION

The previously formulated cross-layer optimization problem can be solved using iterative optimization or decision tree approaches, where a group of strategies are optimized while keeping all other strategies fixed, and this process is repeated until convergence. For the optimization of each group of strategies, one can use derivative and nonderivative methods (e.g., linear and nonlinear programming). Since this is a complex multivariate optimization with inherent dependencies (across layers and among strategies), an important aspect of this optimization is determining the best *procedure* for obtaining the optimal strategy $S^{opt}(\mathbf{x})$. This involves determining the initialization, grouping of strategies at different stages, a suitable order in which the strategies should be optimized, and even which parameters, strategies, and layers should be considered based on their impact on multimedia quality, delay, or power. The selected procedure determines the rate of convergence and the values at convergence. The rate of convergence is extremely important, since the dynamic nature of wireless channels requires rapidly converging solutions (this is illustrated in the example later). Depending on the multimedia application, wireless infrastructure, and flexibility of the adopted WLAN standards, different approaches can lead to optimal performance. A classification of the possible solutions is given in the next subsection.

CLASSIFICATION OF CROSS-LAYER SOLUTIONS

To gain further insights into the principles that guide cross-layer design and to compare the various solutions, we propose the following classification of the possible solutions based on the order in which cross-layer optimization is performed:

Top-down approach — The higher-layer protocols optimize their parameters and the strategies at the next lower layer. This cross-layer solution has been deployed in most existing systems, wherein the APP dictates the MAC parameters and strategies, while the MAC selects the optimal PHY layer modulation scheme.

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[2] *A maximum of 2256 bytes for each video packet has been imposed.*

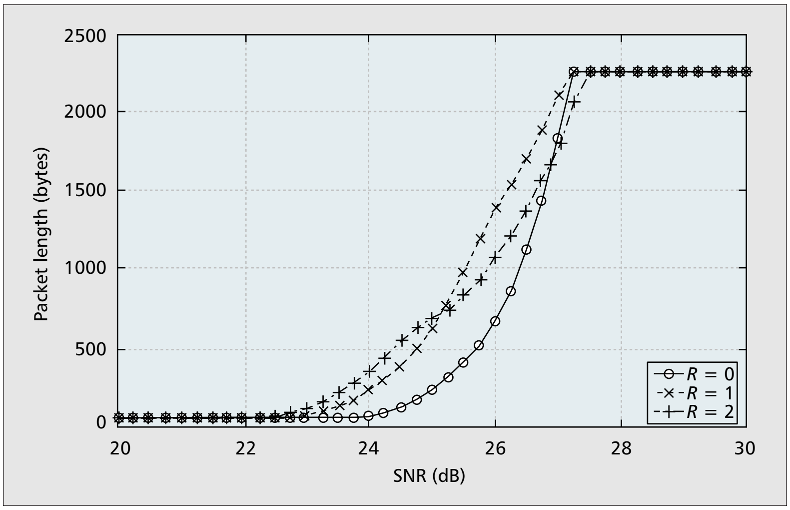

Figure 2. *APP-layer packet length as a function of SNR [10].*

Bottom-up approach — The lower layers try to insulate the higher layers from losses and bandwidth variations. This cross-layer solution is not optimal for multimedia transmission, due to the incurred delays and unnecessary throughput reductions.

Application-centric approach — The APP layer optimizes the lower layer parameters one at a time in a bottom-up (starting from the PHY) or top-down manner, based on its requirements. However, this approach is not always efficient, as the APP operates at slower timescales and coarser data granularities (multimedia flows or group of packets) than the lower layers (bits or packets), and hence is not able to instantaneously adapt their performance to achieve an optimal performance.

MAC-centric approach — In this approach the APP layer passes its traffic information and requirements to the MAC, which decides which APP layer packets/flows should be transmitted and at what QoS level. The MAC also decides the PHY layer parameters based on the available channel information. The disadvantage of this approach resides in the inability of the MAC layer to perform adaptive source channel coding trade-offs given the time-varying channel conditions and multimedia requirements.

Integrated approach — In this approach, strategies are determined jointly. Unfortunately, exhaustively trying all the possible strategies and their parameters in order to choose the composite strategy leading to the best quality performance is impractical due to the associated complexity. A possible solution to solve this complex cross-layer optimization problem in an integrated manner is to use learning and classification techniques (see [11] for our preliminary work in this area). For this, we identify content and network features that can easily be computed and are good indicators of which composite (integrated) strategy is optimal.

The above cross-layer approaches exhibit different advantages and drawbacks for wireless multimedia transmission, and the best solution depends on the application requirements, used protocols, and algorithms at the various layers, complexity and power limitations, and so on. Next, we give several simple illustrative examples of how to perform cross-layer optimization, highlighting the improvements in multimedia quality and power consumption. Next, we show how the APP, MAC, and PHY layers can cooperate in determining the optimal strategy at the PHY layer for multimedia quality and power consumption, respectively. We then illustrate the interactions and trade-offs between various strategies deployed at the MAC and APP layers.

APP-MAC-PHY INTERACTION FOR SELECTING THE OPTIMAL MODULATION SCHEME

Here we show how the APP, MAC, and PHY layers can cooperate in selecting the optimal PHY modulation strategy resulting in the highest multimedia quality. Currently, link adaptation is performed by selecting the optimal modulation scheme that maximizes the throughput of the wireless channel, while simultaneously increasing the robustness of the MAC frame. (Note that in this article the terms MAC frame and MAC packet are used interchangeably). This link adaptation optimization can be formulated as

$$S^{opt}(\mathbf{x}) = \arg\max_{S} Throughput(S(\mathbf{x})), \qquad (4)$$

with $S(\mathbf{x}) = m$, m being the various modulation strategies.

Figure 3 shows the maximum effective throughput obtained using different PHY mode selections for different SNR values. (To determine the instantaneous channel condition, the transmitter uses the received signal strength indicator [RSSI] of the previously received acknowledgment, ACK, frame.) From [12] and Figs. 3a and 3b, it is easy to see that the higher-rate PHY modes result in better throughput performance in the high SNR range, while the lower-rate PHY modes are better for the low SNR range. Another observation from Fig. 3 is that a smaller packet size results in lower effective throughputs due to the fixed amount of MAC/PHY layer overheads for each transmission attempt. Consequently, the MAC can select the modulation strategy m at the PHY that maximizes the throughput. However, the modulation strategy m selected by the MAC-PHY is not always optimal for multimedia applications. The reason for this suboptimal performance is that the MAC-centric optimization focuses only on throughput optimization and does not consider the resulting distortion impact. Hence, the impact on multimedia quality (distortion) needs to be explicitly considered for the cross-layer optimization.

The cross-layer optimization problem can be formulated as follows. Given channel conditions $\mathbf{x}$ (e.g., in terms of SNR), determine the APP-layer rate of the base layer, R_{bl}, and enhancement layer rate, R_{el}, MAC-layer packet size P, and PHY modulation strategy m that maximize the multimedia quality Q (i.e., find the optimal cross-layer strategy)

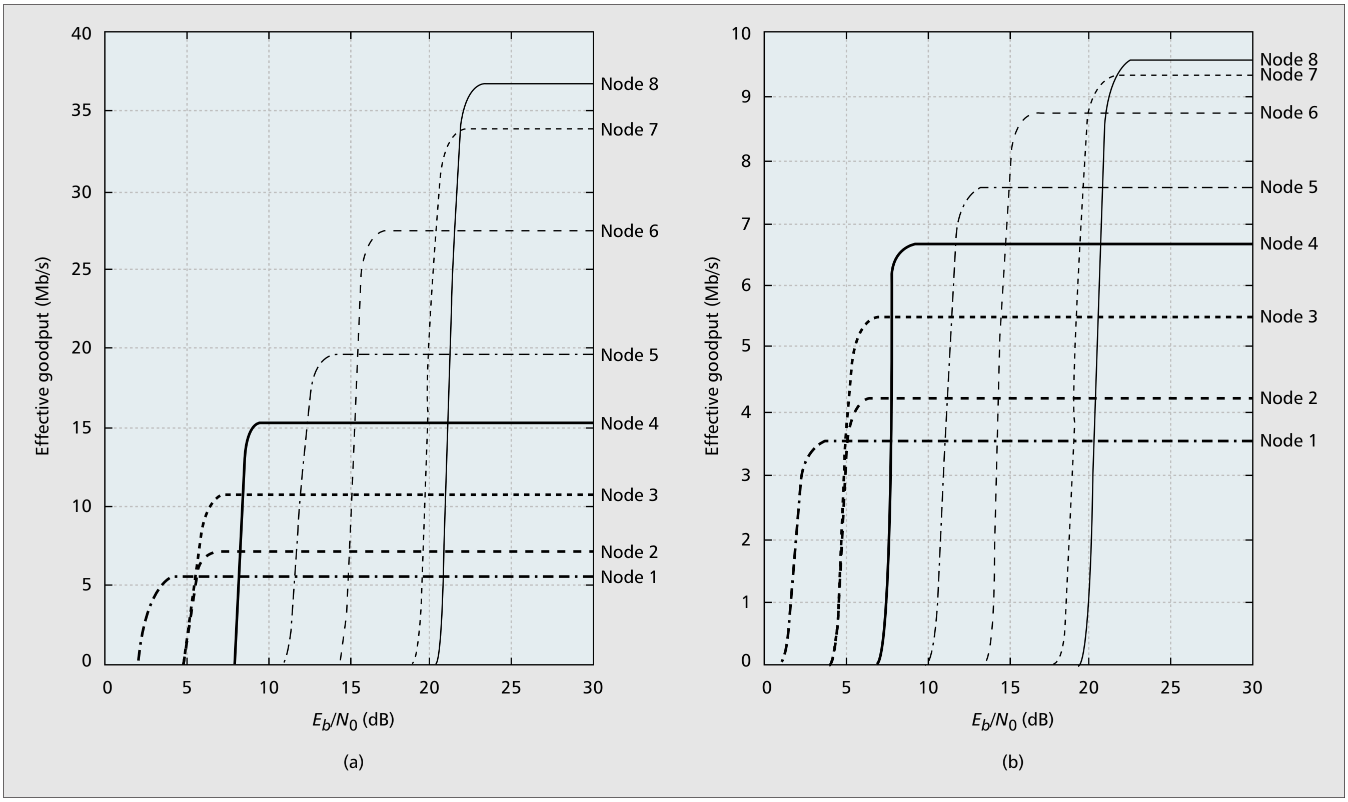

Figure 3. *Optimal modulation scheme as a function of SNR and frame size decided by the MAC [12]: a) MSDU size 2000 octets; b) MSDU size 200 octets.*

$$S^{opt}(\mathbf{x}) = \arg\max_{S} Q(S(\mathbf{x})) \quad \text{with } S(\mathbf{x}) = \{R_{bl}, R_{el}, P, m\}. \tag{5}$$

Figure 4 illustrates the results obtained using the joint PHY-MAC-APP optimization for a video streaming application that can tolerate 1 s delay. The results were obtained using MPEG-4 fine granularity scalability (FGS) [14] and the 802.11b MAC and PHY [15]. For these results, the aforementioned application-centric approach was used, where the APP layer selected the optimal MAC and PHY parameters. Note that by comparing the results from Figs. 3 and 4, different PHY modes were used at various SNRs. Hence, the joint MAC-PHY approach results in suboptimal multimedia performance, and the importance of incorporating the APP layer in the cross-layer optimization for wireless multimedia transmission is clearly highlighted.

A similar conclusion was obtained in [16] for joint packetization and retransmission limit adaptation. Also, in [17] we investigated how several APP and MAC strategies can be jointly optimized to improve multimedia quality. Specifically, we have shown that by jointly optimizing the MAC retry limit along with the application layer rate adaptation and prioritized scheduling strategies, we can maximize the decoded video quality. In determining the optimized joint strategy, we also consider the physical limitations of wireless devices.

We evaluate the impact of these strategies on the perceived video quality by performing a visual experiment according to International Consultative Committee on Radiocommunication (CCIR) Recommendation 500-4 [18]. Since the experiments were conducted at relatively low bit rates and in the presence of packet losses, impairments are expected; thus, the selected five scales for quality measurements are: very annoying (1), annoying (2), slightly annoying (3), perceptible but not annoying (4), and imperceptible (5). The statistical scores summarized in Table 1 clearly illustrate the advantages of cross-layer optimization, as well as highlight the major role played by the APP layer in providing an efficient solution for wireless multimedia transmission. The corresponding peak SNR (PSNR) values can be found in [17].

APP-MAC-PHY Interaction for Optimal Power Consumption

In the previous section we determined the optimal modulation strategy resulting in the best multimedia quality. We now illustrate how to optimize the power consumed for the selected modulation scheme. Let us assume that the wireless channel state can be modeled as a two-state Markov chain with GOOD and BAD states. We can then write the Shannon's capacity theorem as follows:

$$C = \sum_{i=1,2} B \log_2 \left(1 + \frac{P_i a_i p_i}{N_0 B} \right). \tag{6}$$

Here the index i represents the GOOD or BAD states of the channel, and a_i represent the channel attenuation factor for a channel state i. Each channel state occurs with probability

$$p_i \left(\text{i.e.,} \sum_{i=1,2} p_i = 1 \right).$$

Two simple strategies could be deployed for transmission. In the first strategy, the wireless staion (WSTA) could send data only when the channel is GOOD. In the second strategy, the WSTA could use more power to transmit the frame when the channel state is BAD to decrease packet loss. To determine the optimal transmission strategy, we consider the power constraint as follows:

$$P_i p_i a_i \le P_{\max}, \tag{7}$$

where $P_{\max}$ represents the maximum power consumed by the transmitter at the PHY modulation scheme m. Using Kuhn-Tucker sufficient conditions and optimizing Eq. 6 subject to constraint Eq. 7, we have

$$P(h_i) = \left[\frac{1}{\lambda} - \frac{BN_0}{a_i p_i} \right]^{+}. \tag{8}$$

Here λ is the Lagrange multiplier and is obtained from the constraint in Eq. 7. Looking at Eq. 8, it is easy to infer that the optimal strategy involves transmitting at high power when the channel state is GOOD (thus minimizing the frame error probability) and not transmitting or using low power when the channel state is BAD. This is difficult for practical systems, as the channel state has to be known prior to transmission. The other policy that would be intuitive is to use more power when the channel state is BAD and less power when the channel state is GOOD. However, the wireless channel is normally unusable when the state is BAD, and it would require more than $P_{\max}$ to ensure optimal multimedia quality. This scheme also has the same problem as the first scheme: one needs to know the channel quality in advance. Thus, we can conclude that using constant power in both channel states leads to the best performance, as it yields a very low frame error probability when the channel state is GOOD and a lower frame error probability when the channel state is BAD than the strategy of using low power. Additionally, the complexity of determining the channel state is eliminated using this policy. Hence, the deployed power strategy is solely determined by the constraint in Eq. 9.

FAIRNESS FOR WIRELESS MULTIMEDIA TRANSMISSION

In wireless multimedia transmission systems, the cross-layer strategies adopted by the various WSTAs impact other competing stations. Currently, the cross-layer optimization is performed in isolation at each WSTA. However, if a WSTA is adapting its strategy, the delay and throughput of the competing stations are affected; as a consequence, they may need to adjust their own strategies. Hence, the cross-layer strategies adopted by a station should not be optimized in isolation, but should also consider the system-wide availability of resources and "fairness" issues. To illustrate this interaction among stations and their cross-layer strategies, we consider the implementation of the fairness concept in WLANs using a simple example.

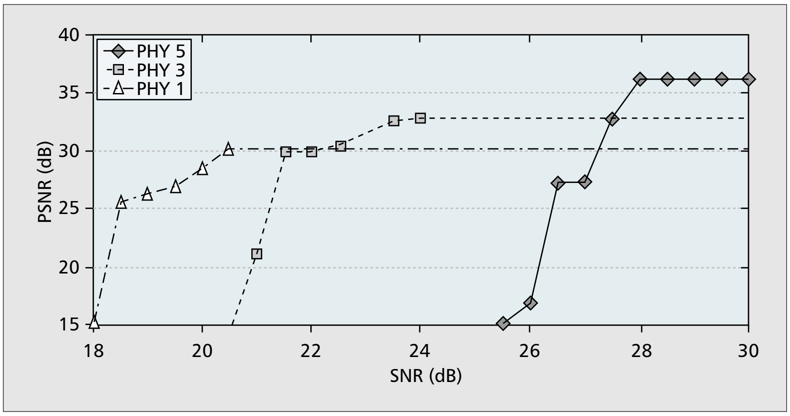

Figure 4. *Optimal modulation scheme decided by the APP-MAC-PHY as a function of SNR [13].*

Deployed strategies	Visual score
No optimization at MAC and APP	1.4
MAC layer optimization (RTRO)	1.9
APP layer optimization	3.8
Joint APP-MAC optimization	4.6

Table 1. *Subjective video quality experiment.*

WHY ARE CURRENT FAIRNESS STRATEGIES NOT SUITABLE FOR CROSS-LAYER OPTIMIZED MULTIMEDIA TRANSMISSION?

The objective of fair scheduling is to provide multimedia applications with different amounts of "work" (resources) proportional to their requirements in terms of bandwidth, delay, and packet loss rates. Usually, work is measured by the amount of data transmitted (in either number of bytes or packets/frames) during a certain period of time. Let $W_i(t_1, t_2)$ be the amount of video flow i's traffic served in a time interval (t_1, t_2), and ϕ_i be its corresponding weight based on its requirements. Then an ideal fair scheduler (i.e., the generalized processor scheduler, GPS [19]) for N WSTAs (and their flows) can be defined as follows:

$$\frac{W_i(t_1,t_2)}{W_j(t_1,t_2)} \ge \frac{\phi_i}{\phi_j}, j = 1, 2, \ldots, N, \tag{9}$$

for any multimedia flow i that is continuously backlogged (backlogged means flow i has frames in its buffer during the specified time interval (t_1, t_2)) during (t_1, t_2). If all multimedia flows are transmitted at a fixed rate, we can obtain from Eq. 9

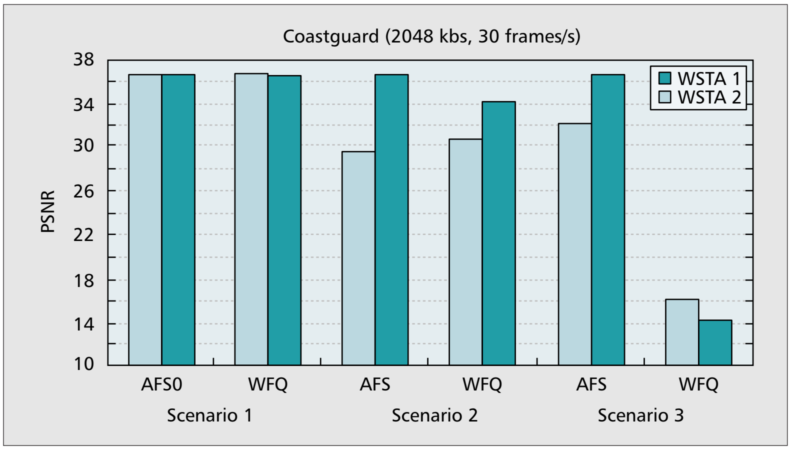

Figure 5. *The PSNR performance of multimedia for different fairness scenarios [20].*

$$\frac{W_i(t_1,t_2)}{t_2-t_1} \geq \frac{\phi_i}{\sum_j \phi_j} r, \tag{10}$$

where r is the physical transmission rate or total channel capacity. Thus, each multimedia flow i is guaranteed to have the throughput given by Eq. 10 regardless of the states of the queues and frame arrivals of the other flows. However, the advantages of using GPS, such as guaranteed throughput and independent service, cannot be preserved if the flows deploy different cross-layer optimization, resulting in different transmission rates. Depending on the channel condition or their distance from the access point (AP), WSTAs may choose different cross-layer transmission strategies (PHY modes, retry limits, frame sizes, etc.) to ensure optimized multimedia quality. Determining a *fair share of resource* among WSTAs in such a transmission scenario is a very challenging problem, because serving an equal amount of traffic from individual stations deploying different strategies requires allocation of various amounts of air time and results in different impacts on the multimedia quality.

AIR OR TIME FAIRNESS

We measure the total throughput degradation due to WSTAs deploying different cross-layer strategies (e.g., different PHY rates) in the WLAN network. Given n WSTAs (with all stations having the same frame size), with

$$n_i\left(\sum_{i=1}^{8} n_i = n\right)$$

operating at, say, PHY mode $i = (1, \ldots, 8)$, the throughput degradation can be determined as [20]

$$Throughput = \frac{1}{\frac{1}{n}\left(\sum_{i=1}^{8}\frac{n_j}{R_j}\right)}. \tag{11}$$

WSTAs having different transmission rates R_j due to the different PHY modes or other deployed cross-layer optimization strategies cause this unfairness. To solve this problem, we propose the concept of time fairness. In this concept each WSTA is given a fair share of time proportional to, for example, the requirements mentioned in their TSPEC [9], rather than guaranteeing the bandwidth. This time allocation (e.g. allocated to a stream at admission time) removes the unfairness due to deploying different cross-layer strategies. Equation 9 can thus be rewritten to impose time fairness as

$$\frac{T_i(t_1,t_2)}{T_j(t_1,t_2)} \geq \frac{\phi_i}{\phi_j}, j = 1,2,\ldots,N, \tag{12}$$

where T_i and T_j represent the time allocated to streams i and j, respectively.

The advantages of the proposed air fair scheduler (AFS), [21], as opposed to the conventional weighted fair queuing (WFQ), are highlighted in Fig. 5.

In the first scenario, the same cross-layer strategies, resulting in the same transmission rate, are deployed for both WSTAs. Thus, WFQ and AFS result in the same PSNR values. Consider the second scenario: WSTA1 experiences more frame errors because of interference and fading. The packet loss rate (PLR) has increased, and it takes on average 50 percent more time to transmit a frame from WSTA1 than from WSTA2. In conventional WFQ, this would mean that the "start-of-service time" of frames in WSTA2 is deferred, resulting in QoS violation and dropping of packets at the MAC layer. This directly affects PSNR performance as most of the higher-priority packets are dropped for both WSTAs. Using AFS, the stream between WSTA1 and the AP alone is affected, yielding low PSNR, whereas WSTA2 is not affected because of WSTA1's channel error condition. In scenario 3 WSTA1 moved far away from the AP, and the cross-layer strategy switched the PHY mode to a more robust modulation scheme. Since the physical transmission rate of WSTA1 has dropped, it would take more time to transmit the frame, and the same problem of deferred start of service happens for both WSTAs in WFQ. However, AFS isolates the channel and differential transmission rates to WSTA1, thus guaranteeing the multimedia performance.

MULTIMEDIA QUALITY FAIRNESS

For multimedia applications, other fair scheduling/allocation strategies could also be identified besides equal time, such as equal multimedia quality and guaranteed minimum quality. To fulfill a certain fairness criterion corresponding information (e.g., traffic characteristics, QoS requirements) and resource exchange strategies for wireless multimedia are necessary.

To understand the potential impact on multimedia quality due to different resource exchanges and corresponding cross-layer adaptation, let us consider the example of multimedia transmission over an IEEE 802.11e network. To fully utilize the features provided by the MAC protocol for multimedia transmission, we propose to use the available application layer information to partition multimedia streams into subflows with different priorities, delay bounds, retry limits, and packet sizes. A base quality subflow can be admitted using an admission control mechanism, while the enhancement subflows can be transmitted in a best effort manner. Our preliminary results in [20] have shown that such a scalable resource allocation can ensure that more users can be simultaneously admitted into the network, while guaranteeing a minimum quality. To illustrate the impact on multimedia quality, we consider that each video emerging from a WSTA is composed of five subflows. In Fig. 6, when all the subflows are admitted the number of stations admitted drops to 9, and increases to 40 when only one subflow admission is made. This number further varies depending on the deployed retry limit at the MAC that results in different PLRs. Depending on the number of admitted subflows at each station, the PSNR can vary between 28 dB (minimum acceptable video quality) and 40 dB (visually lossless video quality). Hence, the admitted sources can decide to trade their quality in order to increase system-wide utilization.

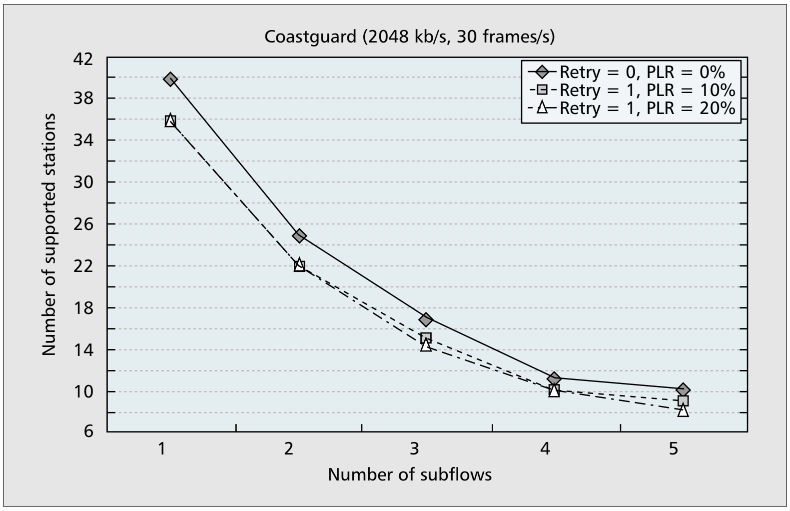

Figure 6. *Number of stations supported as a function of number of subflows [20].*

NEW COOPETITION PARADIGM FOR WIRELESS MULTIMEDIA

As discussed previously, wireless devices currently operate in a non-collaborative manner that limits their performance and overall wireless system performance, as competing stations do not always effectively exploit available resources. Consequently, to improve the performance of wireless multimedia applications, we discuss a new paradigm that fundamentally changes the non-collaborative way in which WSTAs currently interact by allowing them to *exchange information and distribute resources*. The proposed paradigm was inspired by a relatively new and successful economics concept known as *coopetition* [22], which suggests that a judicious mixture of *competition* and *cooperation* is often advantageous in competitive environments. When applied to wireless multimedia systems, coopetition fundamentally changes the *passive* way stations currently adapt their transmission strategies to match available wireless and power resources, by enabling them to *proactively* influence the wireless systems dynamics through resource and information exchange.

For example, two WSTAs experiencing a high PLR over a channel with a high contention level can collaboratively decide to reduce their retry limit or adapt their contention parameters to reduce contention and thus improve their overall multimedia performance and power consumption.

To allow coopetition, we propose a new way of architecting the wireless multimedia communication system by jointly optimizing the protocol stack at each station and the resource exchanges among stations. In the proposed paradigm, information about resources and constraints (e.g., QoS requirements, multimedia traffic characteristics, experienced channel conditions) of the various stations can be disseminated to all network members (stations), and used as available optimization criteria for their own communication subsystem. The proposed coopetition paradigm is a superset of proposed fairness concepts that can be deployed for governing wireless systems more effectively, thereby resulting in improved performance for multimedia applications.

The costs associated with the resource exchange can be quantified in terms of the degradation in multimedia quality, increased delay, or power consumption [23]. For instance, if the resulting multimedia quality Q after the resource exchange is positively impacted, or Q is above a certain maximum quality T_1 (e.g., above 40 dB), the WSTA will contribute its resources. Alternatively, if Q is negatively impacted and below T_1, a penalty will be associated with any resource exchange. If Q is below a minimum quality T_2 (e.g., below 28 dB), the WSTA will stop contributing resources.

Our preliminary results in [24] have shown that coopetition results in an improved number of satisfied users (i.e., station satisfying their minimal quality requirements) compared to de facto allocation of resources. We have designed different coopetition strategies [24] that converge to distinct Nash equilibriums depending on the channel conditions, multimedia application characteristics, resource exchange policies, and so on, resulting in different cost-benefit trade-offs for the participating WSTAs. The design of optimal coopetition strategies together with cross-layer optimized design constitutes a vast topic of further research for improving future wireless multimedia systems.

CONCLUSIONS

The previously described cross-layer optimized wireless multimedia paradigm is only recently emerging, and a variety of research topics still need to be addressed. Realistic integrated models for the delay, multimedia quality, and consumed power of various transmission strategies/protocols need to be developed. Moreover, the benefits in terms of multimedia quality of employing a cross-layer optimized framework for different multimedia applications with different delay sensitivities and loss tolerances still need to be quantified. We have also identified a new paradigm for wireless multimedia transmission based on coopetition, which can result in improved utilization of wireless resources as well as enhanced multimedia performance at participating stations.

The benefits in terms of multimedia quality of employing a cross-layer optimized framework for different multimedia applications with different delay sensitivities and loss tolerances still needs to be quantified.

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ADDITIONAL READING

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BIOGRAPHIES

Mihaela van der Schaar (mihaela@ee.ucla.edu) received the M.Sc. and Ph.D. degrees from Eindhoven University of Technology, Eindhoven, The Netherlands. Starting July 1st, 2005, she is an Assistant Professor in the Electrical Engineering Department at University of California, Los Angeles. Between 1996 and June 2003, she was a senior researcher at Philips Research in the Netherlands and USA, where she led a team of researchers working on multimedia coding, processing, networking, and streaming algorithms and architectures. In 2003, she was also an Adjunct Assistant Professor at Columbia University. From July 2003 until July 2005, she was an Assistant Professor in the Electrical and Computer Engineering Department at University of California, Davis. Since 1999, she was an active participant to the ISO Motion Picture Expert Group (MPEG) standard to which she made more than 50 contributions and for which she received two ISO recognition awards. She was also chairing for three years the ad-hoc group on MPEG-21 Scalable Video Coding, and also co-chairing the MPEG ad-hoc group on Multimedia Test-bed. She has authored more than 100 book chapters, conference and journal papers in this field and holds 18 granted US patents and several more pending. She has also chaired and organized many conference sessions in this area and was the General Chair of Picture Coding Symposium 2004. She was a guest editor of the EURASIP Special issue on multimedia over IP and wireless networks. She was also elected as a Member of the Technical Committee on Multimedia Signal Processing of the IEEE Signal Processing Society and is an Associate Editor of IEEE Transactions on Multimedia, SPIE Electronic Imaging Journal and IEEE Transactions on Circuits and Systems for Video Technology. In December 2004, she received the NSF Career Award.

Sai Shankar N [SM] (nsai@qualcommm.com) received his PhD degree from the department of Electrical Communication Engineering, Indian Institute of Science, Bangalore, India in the area of ATM networks. In 1998, He was awarded the German Fellowship, DAAD, in the department of mathematics, University of Kaiserslautern, Germany to work on queueing approaches in manufacturing. In 1999, he joined Philips Research, Eindhoven, the Netherlands, where he served as Research Scientist working on various problems involving Hybrid, Fiber, Co-axial Cable (IEEE 802.14) Networks and IP protocols. In the year 2001 he joined Philips Research USA, Briarcliff Manor, NY and worked in the area of Wireless LANs/UWB, Cognitive Radios and Cooperative Communications. He was an active contributor of the wireless LAN standard and has submitted more than 15 proposals in shaping QoS related issues in the IEEE 802.11e. He is also an active participant in the Ultra Wide Band (UWB) working group of WiMEdia alliance and has contributed in shaping the new MAC at the Multi-Band OFDM Alliance (MBOA) forum. To this end he was nominated as one of the five finalists in the innovator of the year category by EETimes. He has been the reviewer of almost all important journals in the area of networking and has chaired lots of conferences. Currently he is with Qualcomm Inc. researching on UWB, Cognitive radios and Cooperative communications. He has authored more than 45 conference and journal papers and holds more than 40 patents.