From *Myth* to Methodology: Cross-Layer Design for Energy-Efficient Wireless Communication

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ABSTRACT
During the last decade, wireless communication has seen a trend towards application diversification leading to a significant growth in users. With the availability of – however energy-limited - nomadic devices and real-time multimedia applications, user demand is shifting from simply asking for higher data rates to more complex requirements in terms of Quality of Service (QoS) and energy-efficiency. In this new context energy management is becoming a key success factor. Optimized energy-efficiency requires an energy management that continuously trades off QoS and energy adapting to varying user expectations and environment dynamics. But, QoS can only be evaluated on top of the whole protocol stack while energy consumption largely appears at the lower layers. To minimize overhead during the transitions between layers, we need to address the problem from a cross-layer perspective. We present a methodology that, based on systematic exploration, effective problem partitioning and minimal cross-layer interface, allows energy management in a cross-layer way, while maintaining efficient layered semantics. Different case studies in the context of wireless LAN (WLAN) for multimedia and data traffic transport are discussed, to show how cross-layer energy management can easily be included in systems running state-of-the-art protocols.

Categories and Subject Descriptors
I.6.3 [**Simulation and Modeling**]: Applications – *performance analysis, signal processing systems, computer-aided design, modeling methodologies.*

General Terms
Algorithms, Performance, Design, Theory.

Keywords
Cross-layer, Energy Management, Power-aware design.

1. INTRODUCTION
The last decade has seen the evolution of wireless communication from simple voice telephony to complex, heterogeneous multimedia services. In the context of energy-limited nomadic computing devices (SmartPhones, PDAs, laptops), user demand is shifting from simple data rate increase to more complex requirements in terms of quality of service (QoS) and energy efficiency. It is recognized by the leading industry [1] that current users are more interested in longer battery lifetime and guarantied QoS than in extra computational power or communication bandwidth. On the other hand, there exists a gap between the increase in available energy, consecutive to battery technology evolution, and the increase in energy consumed by applications and communication interfaces. Despite the advances in silicon technology and circuit design, the energy demand of application processors embedded in SmartPhones raises. Similary, average power consumption for wireless communication interfaces, in particular wireless LAN (WLAN), is increasing of remaining at a high level (Table 1).

TABLE 1 WLAN INTERFACE POWER CONSUMPTION [2]

Mode	*802.11b*	*802.11a*	*802.11g*
Sleep	132 mW	132 mW	132 mW
Idle	544 mW	990 mW	990 mW
Receive	726 mW	1320 mW	1320 mW
Transmit	1089 mW	1815 mW	1980 mW

Bridging this energy gap requires to increase by at least one order of magnitude the energy efficiency of wireless communication interfaces. Since technology scaling and circuit design progress are not sufficient, system-level energy management [3] is key to meet this target. For optimum energy-efficiency, a continuous trade-off between QoS and energy is required subject to varying user expectations and environment changes. State-of-the-art system-level energy management for wireless interfaces can roughly be classified in two categories:

Top-down approach Here [3, 4, 5], energy management is carried out as for any other component of the application. In initial wireless interface implementations, circuit power hardly depends on the operation parameters (modulation order, code rate, transmit power). Hence, minimizing the duty cycle and switching into a low-power doze, park, or deep-sleep [6] mode when no communication is needed, saves energy. The key is to design a policy that decides about when to switch into low-power mode, taking into account the utilization profile and the significant time and energy overhead to recover from doze or deep-sleep [4]. However, this kind of energy management is becoming ineffective when the network is heavily loaded (due to broadcast traffic) or when the purpose is multimedia streaming (due to traffic periodicity) [7].

Bottom-up approach In the bottom-up approach, link adaptation [8] and packet scheduling [9] are used to minimize the average power while adapting the transmit rate to the traffic constraints. In the related work, it is always assumed that the power consumption is monotonic with the transmit power, which is convex with the transmit rate. Under that assumption, transmission must occur as slow as allowed by the traffic constraints in order to minimize the aggregate transmit power, essentially maximizing the duty cycle.

These approaches are clearly contradictory. The contradiction comes from the initial assumption – rate-independent power vs. convex power-rate dependency. Only the first hypothesis is valid. Hence, to make the bottom-up approach effective, specific design techniques – energy-aware design [10] – must be applied to provide the convex relation between power consumption and rate. Since the power consumption of some other components appears rate-independent, ideally, a combination of both approaches is required.

Cross layer energy management Trading off QoS and energy-efficiency is, in essence, a cross-layer problem: QoS can only be evaluated on top of the whole protocol stack while energy consumption is mainly concentrated in the lowest layers. Also, when exploiting system dynamics to save energy, it is needed to track variations across the layers. The traditional early divide and conquer approach that leads to independent design of RF front-end, digital baseband, and protocol has proven to result in high design margins and hence low energy efficiency and little adaptability to service, traffic and environment dynamics. An interdisciplinary approach exploiting the interaction between the layers is required. However, a layered structure is still mandatory to guarantee effective deployment of the proposed solution in integrated devices. Unconstrained cross-layer design may lead to undesired side effects that hamper both performance and energy-efficiency [11].

In this paper, we present a methodology, based on systematic exploration, effective problem partitioning and minimum cross-layer API, to enable cross-layer energy management while maintaining efficient layer-based semantics. After describing the main principle of the methodology (Section 2), we show, based on WLAN case studies, how energy-awareness can be increased in the lowest layer (Section 3) and exploited in a cross-layer way (Sections 4, 5) to enable effective energy management that improves significantly the system-level energy efficiency.

2. METHODOLOGY FRAMEWORK

The actual cross-layer energy management problem consists of finding the system operation parameters (configuration) that minimizes the average system energy consumption under quality of service (QoS) constraints. Utilization and environment dynamics are exploited as much as possible to obtain energy gains, for example exploiting channel diversity. QoS can be defined just beneath the application layer but remains application-dependent. For non-real time applications, relevant QoS metrics are net average data rate and latency. For real-time applications with hard deadlines, an effective QoS metric is deadline miss rate.

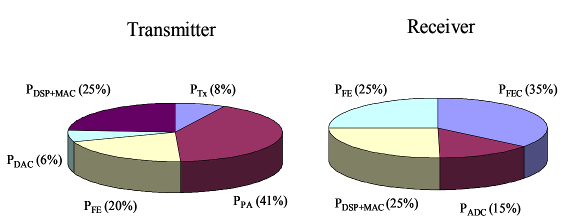

Figure 1 Energy consumption in typical wireless transceivers. Based on state-of-the-art 802.11a WLAN chipsets [12, 13].

In wireless communication interfaces, energy is mainly consumed by the radio circuitry. Fig. 1 describes the typical power breakdown for an IEEE 802.11a compliant WLAN transceiver. Analog front-end and power amplifier (PA) dominate transmission while the reception is determined by the digital signal processing (DSP/MAC + FEC).

Fundamental techniques Designing an effective run-time energy management policy requires understanding and modeling at design-time the relations between the low-level operation parameters, the system-level energy consumption and QoS metrics. Those relations must reflect the cross-layer interactions and may therefore be very complex. To manage complexity and to allow simple and maintainable implementation, it is necessary to keep a layered approach. Importantly, our methodology covers the entire trajectory from specification to implementation of the run-time controller. This approach combines several techniques (Fig. 2): (a) performance-cost modeling; integrated into or underneath a packet-level simulator [14]; (b) packet-level simulation (layer 2 and upwards); in our research, we use ns-2 [15]; (c) scenario-based design in wireless systems [16]; (d) multi-objective Pareto-optimization [17]; (e) dependency analysis and factorization, and finally (f), design-time vs. run-time complexity trade-off.

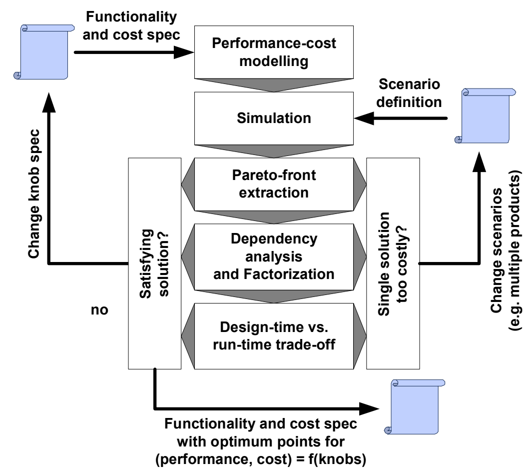

Figure 2 Methodology from design-time exploration to the design of the run-time controller.

Starting from a functionality and cost specification, system performance and cost are modeled. Given initial scenarios, performance-cost trade-off characteristics can be extracted from simulation. Importantly, we may consider now all combinations of adjustable or available dynamics in the system and its environment.

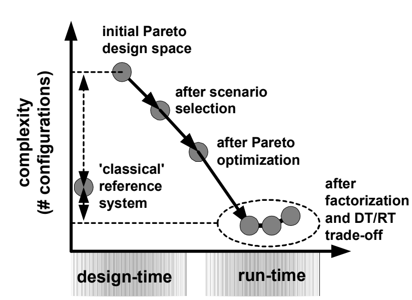

Figure 3 Schematic overview of the evolution of system complexity as a function of considered configurations.

This may lead to an explosion of the design space complexity in terms of possible system configurations (Fig. 3). A first pruning may be applied through pruning those scenarios that are very infrequent or lead to extreme costs through evaluating the cost. Pareto-optimization reduces the multi-dimensional Pareto design space to a significantly less complex Pareto hyper-surface. Finally, factorization can decompose the joint solution space into independent partial solution spaces that can be combined at run-time. Discretization allows for a design-time/run-time trade-off. This flow delivers the optimum set of configurations and hence an improved functionality-cost specification.

Usage models of our design flow Cross-layer design approaches face often criticism as being only applicable for the design of new systems. We believe that most of this criticism originates from the lack of clear design steps in previous approaches. In our methodology, we cover the entire design cycle from early exploration over optimisation towards the low-complexity implementation of the controller in discrete target-oriented steps. Depending on the starting point, more or less parts of our flow can be used effectively by the designer to assess, improve, or explore system performance vs. cost (Table 2). For an existing system, the focus may be on the optimum usage of the given resources and hence e.g. result in minimizing energy for the performance.

TABLE 2 USAGE MODELS OF THE DESIGN FLOW.

Case	*Main objective*	*Main focus*
Existing design	Evaluate performance for different scenarios	Modeling, simulation
Partial redesign	Find performance-cost enhancing knobs	Pareto-front analysis
New design	Find Pareto-optimal component specs	All steps

For a partial redesign, the optimum specifications of a new IP block may be derived or the impact of an available IP block may be assessed. Finally, our approach – in explorative mode - addresses the full cross-layer design space exploration and optimisation problem. Hence, the proposed design steps are suitable both for the optimisation of existing systems as well as for the exploration and definition of partially or entirely new systems.

Changing specifications In case exploration results may not be satisfying, we can either adapt functionality/cost specifications or the scenario side. From these results, we can both identify over-designed as well as under-performing components in the system. Typically, type, granularity or tuning range for these system parameters (*knobs*) need to be adapted. Section 3 illustrates the enhancement of performance-cost characteristics. Since we apply scenario-based design principles, we also evaluate the probability of occurrence for particular configurations. This allows the pruning of irrelevant configurations in case of low probabilities or the split of scenarios in case of too high costs; the latter may lead to a decision for multiple products (high-end vs. high-volume low-cost derivatives).

Reduced-overhead layering through factorization Cross-layer design does not mean the disappearance of any layered structure. Instead, a new layering is proposed with a minimum overhead in communication between layers (Fig. 4). This layering is based on a dependency analysis of the parameters that determine all tasks in a protocol stack and their subsequent factorization into separate performance-cost relationships.

The lowest abstraction layer handles transceiver parameters to maximize energy efficiency under performance constraints. While some information (e.g. channel state information, CSI) has to be provided to the higher layer, the transceiver behavior can be abstracted in Pareto-optimal hyper-surfaces [17]. Inversely, layer II will adapt parameters such as transmit power and linearity through *knobs*. This bi-directional exchange behavior is based on the dependency analysis and factorization results and tries to minimize the number of parameters to exchange. The higher we move on in the protocol stack, the more service-dependent the control behavior becomes. At the highest abstraction layer, average latency and rate constraints are set to satisfy QoS constraints depending on the application: if a bulk TCP transfer is considered, the average TCP rate is considered; for real-time applications, deadline miss rate on top of UDP is relevant. Similarly, depending on the usage policy and the service requirements, the actual information used at intermediate layers may differ slightly: e.g. in the case of multi-user traffic, the scheduler requires the CSI information too, while for TCP single-user traffic, this information can be processed at a lower layer.

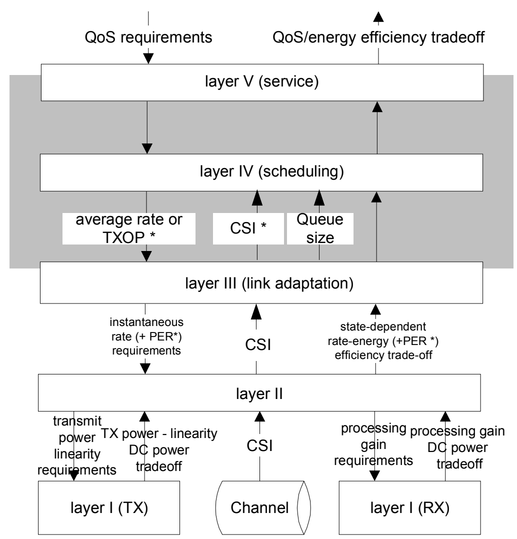

Figure 4 Proposed abstraction layers; in the gray-shaded section differences occur depending on the service. (*) illustrates little extensions or differences required for UDP-based multimedia streaming as compared to TCP random-data traffic.

The behavior of a subjacent layer is always abstracted for the upper layer as a state-dependent hyper-surface between the intermediate performance metrics defined in its API and energy efficiency. Local optimization within an abstraction layer tends to achieve Pareto-optimal tradeoff in this space, resulting in a Pareto set of working points. For each state, the upper layer only needs to know the coordinates of these working points in the (intermediate) performance metrics vs. energy-efficiency space. A run-time control architecture of low complexity is the result.

Architectural view of the run-time device (QoE) manager The design-time process results in a set of optimum configuration points and a policy on how to choose these points. From an architectural point-of-view, we foresee each individual device equipped with a QoE manager (QoEM) that implements the control policy and accesses a run-time database that can be programmed with the optimum configurations derived at design-time (Fig. 5). The QoEM must be able to exchange information with other networked devices across wired or wireless links (e.g. access point, content server) while at the same time it needs access to all *knobs* present in the device components.

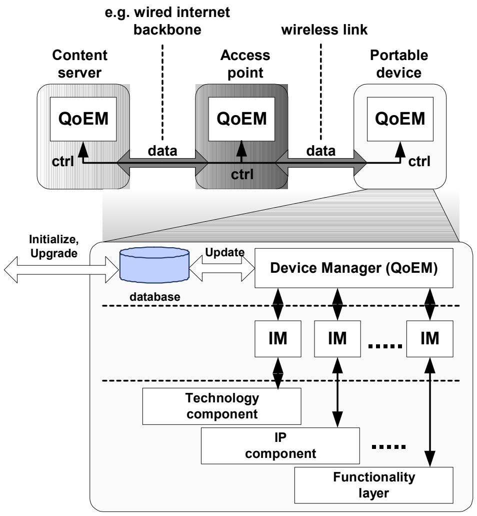

Figure 5 Architectural layering with a central run-time controller per device and assistance through implementation managers per layer or system component.

Components must provide semantically compatible performance-cost characteristics; hence, implementation managers (IMs) are introduced that represent an abstraction layer towards heterogeneous components differing in technology (analog ⇔ digital, hardware ⇔ software), accessibility (IP), or functionality. The IMs offer monitoring (abstraction) and steering (distribution) capabilities to the QoEM.

3. ENHANCING COMPONENT DYNAMICS FOR IMPROVED TRADE-OFFS

In this section, we focus on the lowest abstraction layer defined in Section 2. We address both the dominant transmit and receive components in terms of energy consumption.

3.1 Flexible Transmitter

A convex relation between circuit power consumption and transmit power allows an optimum trade-off between performance and power consumption. In broadband wireless local area networks however, such a relation does not exist a priori [14]. Effective cross-layer energy management therefore requires applying energy-aware design techniques to achieve such a convex relation.

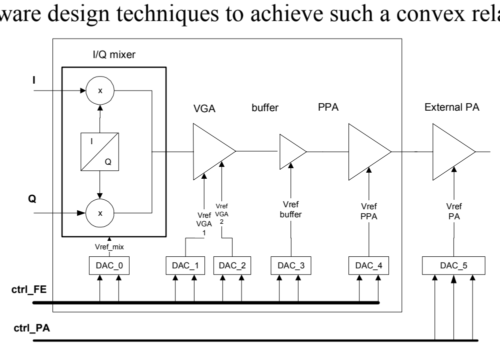

Figure 6 Energy-scalable WLAN transmitter.

An energy-scalable IEEE 802.11a-compliant transmitter is currently being developed (Fig. 6). It contains an adjustable mixer (2-bits configuring the linear gain), a variable gain pre-amplifier (2x2-bit for gain and load control), a buffer (2-bit gain control), a power pre-amplifier (2-bit bias control) and an external power amplifier (3-bit bias control, [18]). $2^{13=2+2+2*2+2+3}$ configurations with different transmit power and linearity (~ $IP3^{-1}$) trade-offs are available. However, only a small set of these configurations lead to a globally Pareto-optimum energy-QoS trade-off.

Fig. 7 depicts the resulting transmitter configurations in the transmit power vs. signal-to-noise-and-distortion (SINAD) ratio vs. circuit power space. SINAD is defined for a dual-tone signal and hence can be interpreted as the classical non-linearity measure IP3. One of these working points will be selected in layer II to provide sufficient linearity to satisfy the EVM constraints for the selected modulation scheme and sufficient transmit power to meet the packet error rate requirements.

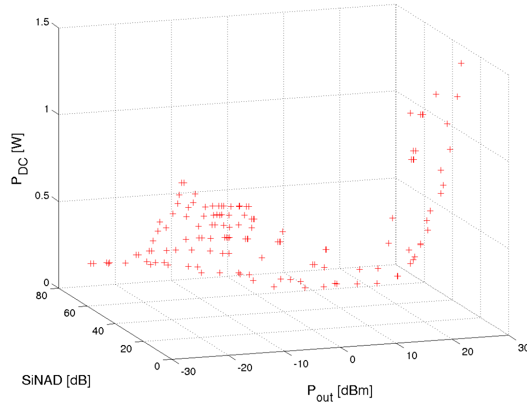

Figure 7 Trading off transmit power P_{out} – SINAD – circuit power P_{DC}.

3.2 Flexible Receiver

At the receiver side, circuit power can be traded off with processing gain. In Fig. 2, it can be seen that almost one half of the receiver circuit power is due to the channel decoder. In recent wireless standards, advanced forward error correction codes based on iterative decoding are considered. In [19], we describe such an energy-aware Turbo codec for WLAN that offers a trade-off range between normalized energy consumption from 0.12 to 1 and processing gain of 4.5 down to 1.9 dB at a bit error rate of 10^{-5} by varying the number of iterations from 6 to 1. Iterative algorithms are also proposed for the complete receive process [20].

4. EXPLOITING LINK DYNAMICS THROUGH RADIO LINK CONTROL

This section focuses on abstraction layers II to IV in the case of a simple link. A time varying channel is assumed. In layer II, the low level control parameters of the transmitter and receiver are set to achieve a given data rate with minimum energy per transmitted bit. The trade-off data rate vs. energy-per-bit depends on the channel. In [21], a discrete channel model is proposed to abstract the behavior of the complicated frequency selective channel encountered with OFDM systems. The channel state is defined as an average path loss and the belonging to a channel *class*. The latter represents how the capacity of a channel instance relates to the average capacity for similar signal to noise ratio.

For a given channel state, for each modulation and code rate, the minimum transmit power, IP3 and number of decoding iteration to meet the EVM requirements and achieve vanishing packet error rate can be uniquely determined [21]. From the layer-I Pareto surfaces, those transmit power, IP3 and number of iterations requirements can be related to a transceiver circuit power and, with the effective data rate, to the energy per bit. Fig. 8 depicts the resulting rate vs. energy-per-bit tradeoff curves for each channel class and an average path loss of 80 dB.

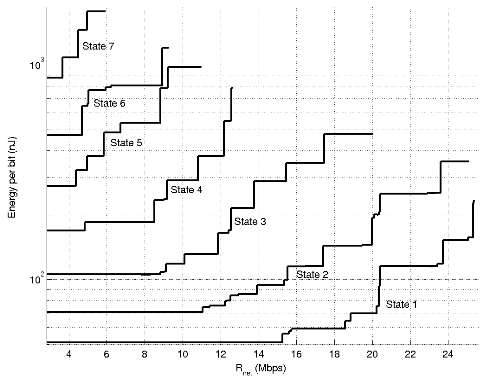

Figure 8 Per-channel state rate vs. energy-per-bit tradeoff for an average path loss of 80 dB.

In the case of a simple link, adaptation to the varying channel is abstracted in the third layer. The latter obtains from layer II information about the current channel state and the tradeoff between rate and energy efficiency in each state. Based on an average rate constraints forwarded by the upfront layer, a mapping of the channel state to the rate-energy working point can be derived [21], from which a trade-off between average rate and average energy-per-bit results. Finally, in layer IV, the dynamics of packet scheduling is considered. With an energy-scalable transmitter, it has been shown in early work [22] that significant energy saving can be achieved by coupling packet scheduling and link adaptation. In [23], we have shown that the corresponding joint packet scheduling - link adaptation policy can be decoupled at very small cost. When applying the decoupled policy, the average rate constraint forwarded to layer IV is set proportional to the queue backlog for the considered link. We have shown that the corresponding system adapts itself to the user data rate while average latency is controlled by the proportional parameter K. Fig. 9 depicts the resulting average-rate vs. average-latency tradeoff for several input rates.

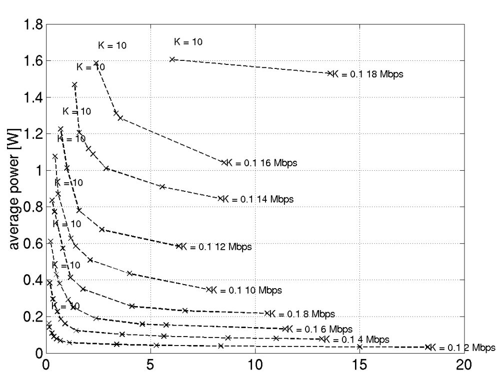

Figure 9 Average latency vs. average energy efficiency.

5. EXPLOITING MULTI-USER DYNAMICS THROUGH SCHEDULING

In this section, we describe how to instantiate our methodology for delay-sensitive video traffic over a WLAN. Video QoS can be measured as a function of Job Failure Rate (JFR), or the percentage of video frames that are not delivered before their deadline (which we assume to be the boundary of the scheduling period). The low level knobs are the ones derived in Section 3. At MAC level, we add the number of retransmissions to better control the JFR, and we allow the system to shutdown at scheduled instances, to eliminate idle and overhearing energy consumption [22]. No time diversity can be exploited because of the hard deadline constraint. We consider here a scenario with multiple variable- bit-rate video streams, where both channel and bit-rate of the different streams vary independently. The task of the run-time controller is then to assign to each user, depending on its current load and channel state, a share of the scheduling period so that it can deliver the frame before the end of that scheduling period with the required probability (1-JFR). To take this decision, the scheduler combines the set of low-level curves that represent the energy-performance trade-off of each user individually, into an aggregate network energy-performance representation. Since the semantics of this scenario are different from the case study in Section 4, a structurally similar yet different-in-detail representation of the same hardware is needed (Fig. 4*). In particular, for this energy-efficient real-time scheduling, the sufficient representation of the lower hardware at layer II consists of the Pareto-optimal points in the energy/packet-rate-PER plane. As some frame losses are tolerated for video, we consider the PER in the optimization problem to potentially save energy. The three-dimensional Pareto-surfaces are generated for each possible channel state as derived above.

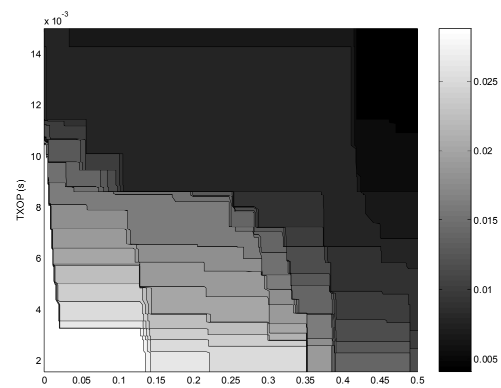

Figure 10 Design space for job-failure-rate (JFR) vs. TXOP vs. energy consumption trade-off (contour plot).

In layer III, we add DLC overhead taking into account the knobs offered there. A first knob is the number of retransmissions allowed before the deadline, to reach the target JFR. Second, given the large energy consumption in idle and receive state (Table 1), we want to put the nodes to sleep as much as possible. Given the information of layer II per channel, we derive the Pareto-optimal points in the energy/job-JFR-TXOP dimension [22]. TXOP denotes the total active time assigned to the transmit node. The result is a database of curves per channel state and job size. The job size is the queue size of the given node, or the number of fragments to be transmitted before the deadline. Fig. 10 shows the curve for an average channel state and job size of 10kB. Increasing the channel resource given to the user (TXOP) or decreasing the JFR constraint both result in energy savings up to a factor of 5 [26]. In layer IV, scheduling is performed to minimize the energy for the given channel states, job sizes and JFRs of each node. First, a convex piece-wise linear energy-TXOP curve is constructed per user based on its JFR constraint. Then, a fast greedy algorithm [23] combines these curves into an instantaneous network energy-scheduling period curve. Fig. 11 illustrates a set of aggregate curves for a network of 1 to 7 users with channel and job size constraints identical per user curve. From this curve, we derive a bounded sub-optimal network resource allocation. The resulting TXOP-per-user is passed onto the lower layers.

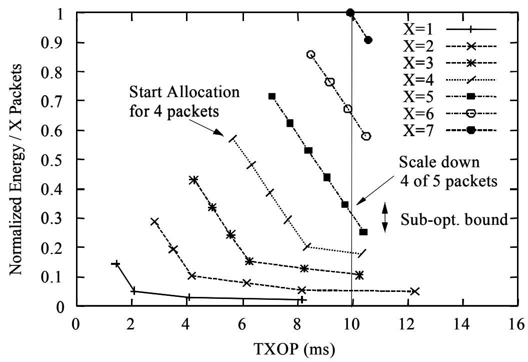

Figure 11 Trade-off including the multi-user aspect.

6. CONCLUSIONS

Exploitation of system and environment dynamics is at the basis of our methodology. Performance in the form of throughput and latency are traded-off against energy consumption as cost. We considered two service types: data traffic over TCP [23] and multimedia streaming based on UDP and MPEG-4 simple profile video encoding [26]. Our methodology suited both cases, allowing a systematic exploration of the design space, a true cross-layer performance-energy trade-off, and using a set of techniques, a low-complexity run-time controller was obtained. The methodology bridges design- and run-time aspects and includes the definition of a generic architectural template.

The next challenge is the extension towards the user who is not aware of the link but interested in a good experience for a selected service mix [25]. This service-link gap is yet another opportunity to exploit dynamics. Service quality can be traded-off against link or network quality and hence against energy consumption. The challenging point is to establish a relation between subjective user perception and measurable network QoS [24]. Structurally, our solution appears easily extendible towards the service-link gap challenges, but further research is required to characterize the quality-cost trade-offs for these and other service types and to identify more underlying commonalities that can simplify the support of true *multiple* services across the wireless network. Together with techniques such as scalable video coding (SVC) [27], cross-layer design based on a strong methodology can open the doors towards new performance-quality-energy trade-offs.

7. ACKNOWLEDGMENTS

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8. REFERENCES

[1] Intel Corp., “Low-power wireless LANs: Past, present, and Future,” panel session, *DATE*, Munich, March 2005.

[2] Dell TrueMobile 1400 WLAN Card.; available on http://support.ap.dell.com/docs/network/p44970/en/specs.html

[3] L. Benini et al., “A Survey of Design Techniques for System-Level Dynamic Power Mgmt,” *IEEE Trans. VLSI*, vol. 8, no. 3, June 2000.

[4] T. Simunic et al., “Energy Efficient Design of Portable Wireless Systems,” *Proc. ISLPED*, pp. 49-54, Italy, Aug. 2000.

[5] R. Zheng and R. Kravets, "On-demand power management for ad hoc networks," *Proc. IEEE INFOCOM*, San Francisco, USA, 2003.

[6] IEEE 802.11 standard, specific parts on power management.

[7] A. Acquaviva, T. Simunic, et al., “Remote power control of wireless network interfaces,” *J. Embedded Comp.*, vol. 3, 2004.

[8] C. Schurgers et al., "Modulation scaling for energy aware communication systems," *Proc. ISLPED*, Huntington Beach, CA, Aug. 2001.

[9] E. Uysal-Biyikoglu, "Energy-Efficient Packet Transmission over a Wireless Link", *ACM/IEEE Trans. Netw.* vol. 10, no. 4, Aug. 2002.

[10] A. Sinha and A. P. Chandrakasan, “Energy Scalable System Design”, *IEEE Trans.VLSI Systems*, pp. 135-145, Apr. 2002.

[11] V. Kawadia, P. Kumar, "A cautionary perspective on cross-layer ,” http://black.csl.uiuc.edu/~prkumar/html_files/publications.html

[12] M Zargari et al., "A 5GHz CMOS Transceiver for IEEE 802.11a WLAN," *IEEE JSSC*, vol. 37, no. 12, pp. 1698-1694, Dec. 2002.

[13] A. Belnad et al., "Direct conv. CMOS transceiver with AFC for 802.11a WLANs," *Proc. ISSCC*, San Francisco, USA, Feb. 2003.

[14] B. Bougard et al., "Energy Scalability Enhancement of WLAN transceivers," *IEEE SPAWC*, Lisboa, Portugal, July 2004.

[15] Network simulator ns-2; available on http://www.isi.edu/nsnam/ns/.

[16] J. Van Driessche, G. Cantone, W. Eberle et al., “Transmitter cost/efficiency exploration for 5-GHz WLAN,” *IEEE Radio and Wireless Conf.*, Boston, USA, Aug. 2003.

[17] K. M. Miettinen, Non-Linear Multi-Objective Optimization, Kluwer Academic Publisher, Boston, 1999.

[18] Microsemi, LX5503 WLAN Power Amplifier datasheet, http://www.microsemi.com/datasheets/lx5503.pdf.

[19] B. Bougard et al., “A scalable (…) parallel concatenated convolutional Turbo-Codec,” *Proc. ISSCC*, San Francisco, USA, Feb. 2003.

[20] M. Tüchler et al., “Turbo equalization: principles and new results,” *IEEE Trans. Comm.,* vol. 50, pp. 754-767, May 2002.

[21] B. Bougard et al., “Energy-aware radio link control for OFDM-based WLAN”, *Proc. IEEE SiPS*, Austin, USA, Oct. 2004.

[22] R. Berry and R. Gallager, “Communication over fading channels with delay constraints,” *IEEE Trans. Inform. Theory*, vol. 48, pp. 1135-1149, May 2002.

[23] B. Bougard et al., “Transport level performance-energy trade-off in wireless networks and consequences on the system-level architecture and design paradigm”, *Proc. IEEE SiPS*, Austin, USA, Oct. 2004.

[24] R. Jain, “Quality of Experience,” *IEEE Multimedia,* vol. 11, no. 1 pp. 95-96, Jan-Mar 2004.

[25] A. van Moorsel, “Metrics for the internet age: Quality-of-Experience and Quality of Business,” *HP Labs report HPL-2001-179,* 2001.

[26] R. Mangharam, S. Pollin, et al., “Optimal fixed and scalable energy mgmt for wireless networks,” *IEEE INFOCOM*, Miami, Mar 2005.

[27] J.-R. Ohm, “Advances in scalable video coding,” *Proc. IEEE*, vol. 93, no. 1, pp. 42-56, Jan. 2005.