Cross-Layer Optimization for Energy-Efficient Wireless Communications: A Survey*

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Abstract—**Since battery technology has not progressed as rapidly as semiconductor technology, power efficiency has become increasingly important in wireless networking, in addition to the traditional quality and performance measures, such as bandwidth, throughput, and fairness. Energy-efficient design requires a cross layer approach as power consumption is affected by all aspects of system design, ranging from silicon to applications. This article presents a comprehensive overview of recent advances in cross-layer design for energy-efficient wireless communications. We particularly focus on a system-based approaches towards energy optimal transmission and resource management across time, frequency, and spatial domains. Details related to energy-efficient hardware implementations are also covered.**

Index Terms– energy efficiency, cross-layer, wireless communications, energy aware

I. INTRODUCTION

The demand for high data-rate multimedia wireless communications has been growing rapidly. As standards are addressing higher capacity wireless links to meet increasing demands, device power consumption is also increasing. Although silicon technology is progressing exponentially, doubling about every two years [1], processor power consumption is also increasing by 150% every two years [2]. In contrast, the improvement in battery technology is much slower, increasing a modest 10% every two years [2], leading to an exponentially increasing gap between the demand for energy and the battery capacity offered. Furthermore, the shrinking device sizes are also imposing an ergonomic limit on the battery capacity available.

As an illustration of the above, Table I from [3] shows that the power consumption of commercial 802.11 transceivers [4] in all operation modes has been increasing with each new standard. The power consumption in the transmit mode will be even higher for long-distance communications, such as in cellular networks. We also expect wireless power consumption to further increase as devices with multiple radio protocols become common. Additionally, as device sizes shrink, wireless power consumption is becoming a dominant part of device power budget. It is shown in [5] that radio interfaces, including bluetooth, Wifi, and cellular communications, account for more than 50% of overall system energy budget. Hence, power efficiency is becoming more and more important for battery-driven wireless mobile communications.

Energy consumption is affected by all layers of system design, ranging from silicon to applications. In this paper, we focus on improving device energy efficiency. The traditional layer-wise approach leads to independent design of different layers and results in high design margins. Cross-layer approaches exploit interactions between different layers and can significantly improve energy efficiency as well as adaptability to service, traffic, and environment dynamics. Recent efforts have been made to tackle energy consumption at all layers of communication systems, from architectures [6]–[8] to algorithms [9]–[11]. Additionally, as wireless is a shared medium, device energy consumption is not only affected by the layers comprising the point-to-point communication link, but also by the interaction between the links in the entire network. Hence, a system approach is required for energy-efficient wireless communications.

TABLE I: Power Consumption of a Wireless Transceiver

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

The *physical* (PHY) layer plays a very important role in wireless communications due to the challenging nature of

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* This work was supported by Intel Corp. and the U.S. Army Research Laboratory under the Collaborative Technology Alliance Program, Cooperative Agreement DAAD19-01-20-0011.

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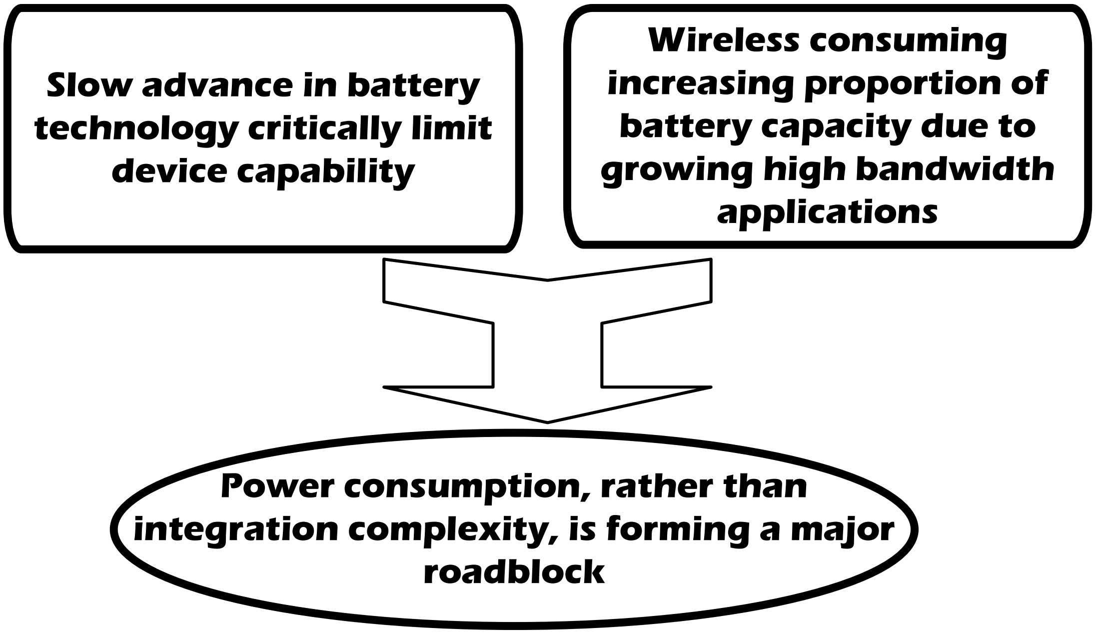


Fig. 1: Energy consumption limits advances in wireless communications

communication medium. The power consumption of wireless devices heavily relies on the PHY layer. The *medium access control* (MAC) layer manages wireless resources for PHY layer and directly impacts overall network performance. Hence, we focus on joint PHY and MAC layers techniques to improve wireless energy efficiency. Readers interested in energy-efficient design for upper-layer protocols are referred to [12]–[23].

The PHY layer deals with data transmission over wireless channels and consists of *radio frequency* (RF) circuits, modulation, power control, and channel coding units, etc. Traditional wireless systems are built to operate on a fixed set of operating points to support the highest feasible PHY rate; therefore, they always transmit the maximum allowable power [24], i.e. no power adaptation. This results in excessive energy consumption for average channel conditions. Hence, a set of PHY parameters that influence the system-level energy efficiency and performance should be adjusted to adapt the actual user requirements (e.g. throughput and delay) and environments (such as shadowing and frequency selectivity) to trade off energy efficiency and spectral efficiency.

The MAC layer ensures that wireless resources are efficiently allocated to maximize network-wide performance metrics while maintaining user *quality-of-service* (QoS) requirements. Here, pessimistic medium access strategies that allocate wireless resources to assure worst-case QoS may hurt network energy efficiency. The MAC layer can enhance energy efficiency using the following three measures.

1) Energy can be saved in mobile devices by shutting down system components when inactive. The MAC can enable inactive periods by scheduling shutdown intervals according to buffer states, traffic requirements, and channel states.
2) The MAC layer controls medium access to assure both individual QoS and network fairness. In distributed access schemes, MAC should be improved to reduce the number of wasted transmissions that are corrupted by interference of other users; while in centralized access schemes, efficient scheduling algorithms should exploit the variations across users, to maximize overall energy efficiency of users in the network.
3) Power management at the MAC layer reduces the standby power by developing a tight coordination between users such that they can wake up precisely when they need to transmit or receive data.

The remainder of this paper is organized as follows. In Section II, we consider energy-efficient communication over a single communication link between the user and the network. Fundamental results for per-link energy-efficient communications are presented from an information theoretic viewpoint, and different energy-efficient transmission techniques across time, frequency, and spatial domains are introduced. In Section III, network level energy-efficient resource management policies are discussed, again focusing on the time, frequency and spatial resources. How the network manages circuit power consumption in the device is also discussed. Next, in Section IV, several efforts on hardware implementation of cross-layer techniques for energy-efficient wireless communications are also addressed. Finally, Section V concludes the paper.

II. ENERGY EFFICIENT TRANSMISSIONS

In this section, we introduce energy-efficient techniques for point-to-point link communications. We first survey key results from information theory and then discuss energy-efficient transmission across time, frequency, and spatial domains.

A. Fundamental issues

Information theorists have studied energy-efficient communications for at least two decades [25], [26]. According to Shannon [27], the capacity of an ideal bandlimited *additive white Gaussian noise* (AWGN) channel approaches

$$R = \lim_{W\to\infty} W \log_2\left(1+\frac{P}{WN_o}\right) = \frac{P}{N_o} \qquad \text{(bits/s)} \quad (1)$$

as its bandwidth goes to infinity, where W is the channel bandwidth, P is the received power, and N_o is the noise spectral density. To save energy, transceivers can be designed to maximize information bits per unit energy in contrast to the information per degree of freedom [28]. However, from the Shannon capacity, energy efficiency can only be obtained at the cost of infinite or huge bandwidth and results in zero or very low spectral efficiency. This qualitative analysis also ignores practical issues with increasing bandwidth: delay spread and frequency selectivity of the channel, phase noise, non-linearity of the power amplifiers and other wideband RF circuits.

As in many communication scenarios, the primary constraint on the transmitted sequences arises from power limitations. The work in [25] defines reliable communication under a finite energy constraint in terms of the capacity per unit energy, which is the maximum number of bits that can be transmitted per unit energy. This definition ensures that for any transmission rates below the capacity per unit energy, error probability decreases exponentially with the total energy. It is also shown that the capacity per unit energy is achieved using an unlimited number of degrees of freedom per information bit, e.g. with infinite bandwidth [28] or long-duration regime communications [29].

The information theoretic results derived in [28], [29] focus only on transmit power when considering energy consumption during transmission. Typically a device will incur additional circuit power during transmission which is relatively independent of the transmission rate [30]–[32]. Thus a fixed cost of transmission is incurred which must be accounted for optimizing energy consumption. In the following sections we will consider the impact of circuit power on the optimal transmission parameters for energy-efficient communication. The focus will also shift towards using optimization theory framework for determining energy optimal link settings.

B. Time-domain energy-efficient transmission

With capacity-approaching channel codes, such as, turbo codes, the data rate of an AWGN channel is given by

$$R = W \log_2(1+\frac{\widehat{P}g}{WN_0}), \quad (2)$$

where $\widehat{P}$ is the transmit power and g is the channel gain. The time to transmit one bit is t and the corresponding data rate is $R=\frac{1}{t}$. Thus the energy consumption per bit is

$$E = \widehat{P}t = \left(2^{\frac{1}{Wt}}-1\right)WN_0 t/g, \quad (3)$$

which is monotonically decreasing and convex in transmission duration t. Since the tradeoff between transmission time and transmission energy is convex, it is necessary to transmit a packet over a longer period of time to save energy. Hence, the lowest order modulation should always be used while accommodating the delay constraint [29] to minimize energy consumption if only transmit power is considered.

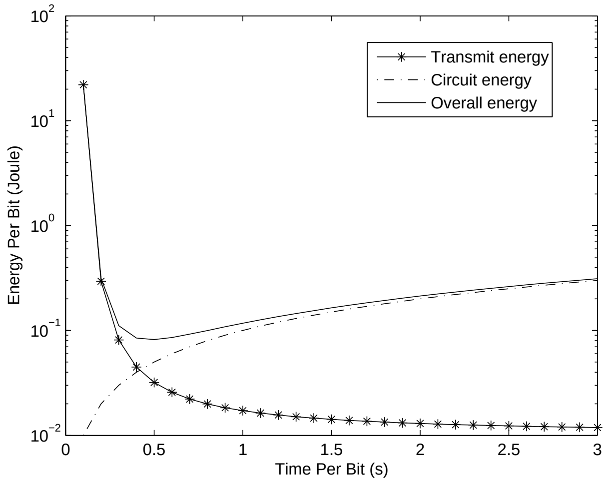


Fig. 2: Relationship between energy consumption and symbol duration

When circuit power is taken into account, the method to transmit with the longest duration is no longer the best any more since circuit energy consumption increases with transmission duration. In this case, the overall energy transmitting one bit turns out to be

$$E = \widehat{P}t + P_c t = \left(2^{\frac{1}{Wt}}-1\right)WN_0 t/g + P_c t, \quad (4)$$

where P_c is the average circuit power, including all electronic power consumption except transmit power for reliable data transmission. Fig. 2 shows circuit energy and transmit energy trade-off for overall energy efficiency. The energy dissipation consisting of both transmitter electronics and RF output is studied in [30], and several energy minimization techniques, including modulation and multiple access protocols, are derived for short range asymmetric micro-sensor systems based on numerical simulation. It is shown that a high-order modulation may enable energy savings compared with binary modulation for some short-range applications by decreasing the transmission time. In [31], these ideas are extended to a detailed energy consumption analysis specifically for both uncoded and coded *M-ary quadrature amplitude modulation* (M-QAM) and *multiple frequency shift keying* (MFSK) in AWGN channels. Therefore, energy-efficient transmission is formulated to find tradeoff among transmission energy, circuit energy consumption, and transmission time. Similarly, a steepest descent gradient algorithm is designed to search the optimal rate that minimizes the average power consumption subject to a constraint on an average throughput in [33].

C. Frequency-domain energy-efficient transmission

As indicated above, transmitting with infinite bandwidth will achieve the highest energy efficiency. However, system bandwidth is, in general, limited. Furthermore, different frequency bands usually experience different fadings, which is why *orthogonal frequency division multiplexing* (OFDM) becomes a key modulation scheme for next generation broadband wireless standards [34], [35]. While extensive research has been conducted to improve throughput [36], [37], limited work has been done to address energy-efficient communication over frequency-selective channels using OFDM.

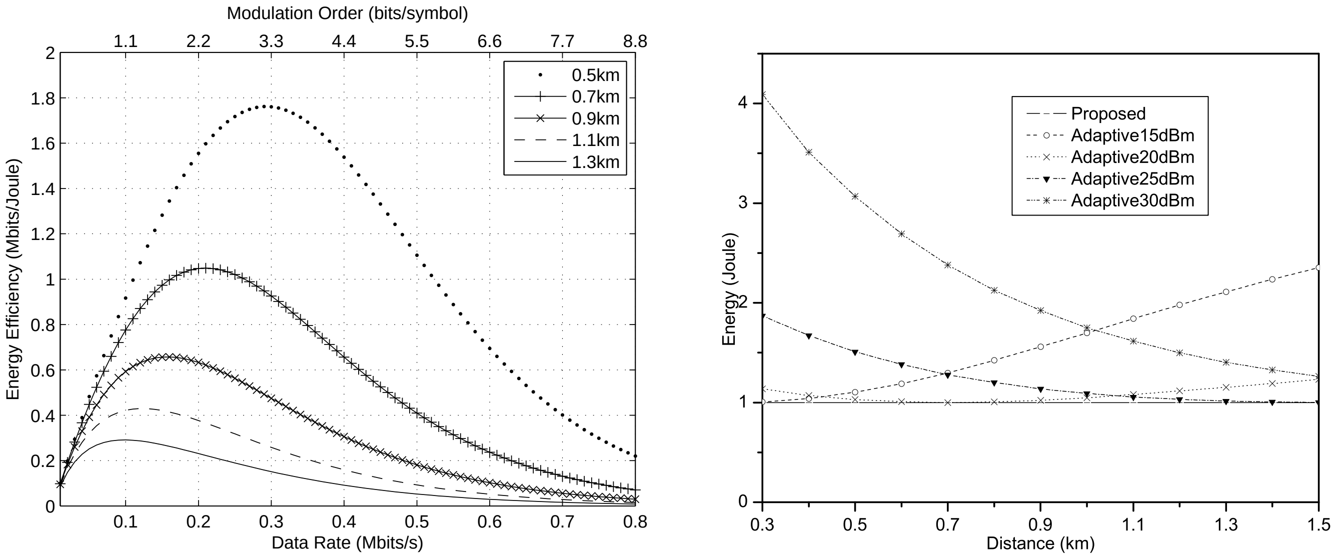
Our preliminary results on energy-efficient transmission in uplink *orthogonal frequency-division multiple access* (OFDMA) systems for mobile stations are shown in Fig. 3. Both circuit and transmit powers are considered when designing link adaptation and resource allocation schemes. As a first step investigation, we have addressed the case of flat-fading channels [32]. We show that for energy-efficient transmission, both assigned data rate and energy efficiency increase with channel gain. Furthermore, the modulation order on each subchannel should decrease with the number of subchannels assigned to a user while the energy efficiency increases. Figure 3(a) illustrates energy efficiency of users at different distances from the *base station* (BS). The lower axis shows the data rate while the modulation order is indicated on the top axis. By selecting an optimal modulation scheme, energy efficiency increases as the user moves closer to the BS. The closer the user is to the BS, the higher should be the modulation order used. Figure 3(b) compares the optimal energy-efficient schemes with traditional adaptive modulations. In traditional adaptive modulation, the transmit power is fixed at 15 dBm, 20 dBm, 25 dBm, or 30 dBm. The energy values are normalized with those of the proposed optimal energy-efficient scheme. By varying both modulation order and transmit power allocation, the proposed method always achieves the lowest energy consumption.

In [38], we address energy-efficient link adaptation for frequency-selective fading channels. Different from existing water-filling power allocation schemes that maximize throughput subject to overall transmit power constraint. The scheme adjusts both overall transmit power and its allocation according to the states of all subchannels and circuit power consumption to optimize energy efficiency. We have found the necessary and sufficient conditions for unique globally optimal link adaptation. According to our study, a subchannel is used only if the overall per bit energy consumption when it is idle is bigger than the per bit energy consumption when transmitting at an infinitely small data rate on the subchannel assuming that the status of all the other subchannels is optimal. If data are transmitted on a subchannel, the power allocation and modulation depends on both the circuit power consumption and transmission on all other subchannels. We develop iterative methods for the optimal link adaptation. Simulation results show at least a 15% improvement in energy utilization when frequency selectivity is exploited and the improvement depends on how much frequency diversity exists within the channels.

D. Spatial-domain energy-efficient transmission

Multiple-input and multiple-output (MIMO) techniques have been shown to be effective in improving wireless system capacity and spectral efficiency. However, the advantage of MIMO technique comes with an overhead in circuit implementation due to duplicated transmitter and receiver radio front ends. With increased spectral efficiency, smaller transmission duration is needed and this reduces both transmit power and circuit power consumption. The exploitation of multiple antennas requires more active circuit components, which increases both transmit power and circuit power. Hence, characterizing how multiplexing gain, diversity gain, and circuit cost impact overall system energy efficiency is important.

How MIMO techniques affect energy efficiency has been addressed recently in [39]–[42]. As circuit energy is dependent on the numbers of transmit and receive antennas, it is shown that for short-range transmission, MIMO decreases energy efficiency as compared with single antenna transmission if they are not combined with adaptive modulation [39]. However,



(a) Relationship of energy efficiency, distance, modulation, and transmission rate (b) Normalized energy consumption on transmitting one million bits

Fig. 3: Link-level energy-efficient transmissions

by adapting the modulation order to balance transmit energy and circuit energy consumption, MIMO systems outperform *single-input single-output* (SISO) systems, as shown in Fig. 4 according to [39]. In a similar context, diversity-multiplexing trade-off for energy efficiency is investigated in [40], [42]. It is also shown that further energy efficiency improvement is achievable by adapting multi-antenna encoding to channel conditions. In [42], space-division multiplexing [43], space-time coding [44], and the number of active antennas (an extreme form of precoding) are adapted to the channel state, on a packet-by-packet basis, to improve energy efficiency. An improvement in both link energy efficiency (up to 30%) and throughput (up to 50%) can be observed with this spatial-domain energy-efficient link adaptation.

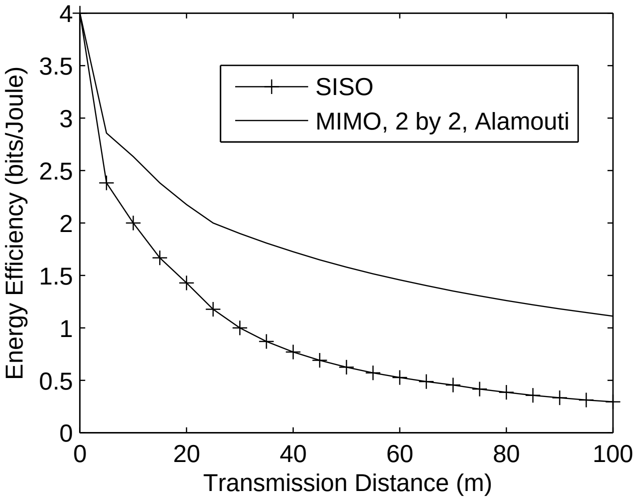


Fig. 4: Comparing energy consumption of MIMO and SISO

III. NETWORK ENERGY EFFICIENT RESOURCE MANAGEMENT

Wireless resources are managed by MAC protocols. MAC protocols can be classified into a few basic categories. For centralized MAC, base stations or central schedulers perform access control allocating network resources. For distributed MAC, random access schemes determine access opportunities of users. Due to limited wireless resources, there exist intricate tradeoffs between individual performance and the whole network. For example, in a *time-division multiple access* (TDMA) system, all users share a common frequency band. Lowering the rate of one user requires longer transmission duration and thus reduces the available time of other delay-sensitive users. This forces other users to increase modulation order to support higher data rate and consume more energy while potentially the transmission may still suffer from a higher *bit-error rate* (BER). Flexible cross-layer optimization allowing each user to adapt to its environment will enable huge energy savings. Furthermore, the exploitation of diversity across all users will further reduce overall network energy consumption. In this section, we will introduce energy-efficient wireless resource management policies considering time, frequency and spatial resources. Also covered are techniques, which are targeted towards reducing circuit power consumption through maximizing idle and sleep time for each user.

A. Circuit resource management

As circuit power occupies a large portion of overall energy consumption, effective circuit power management policies are

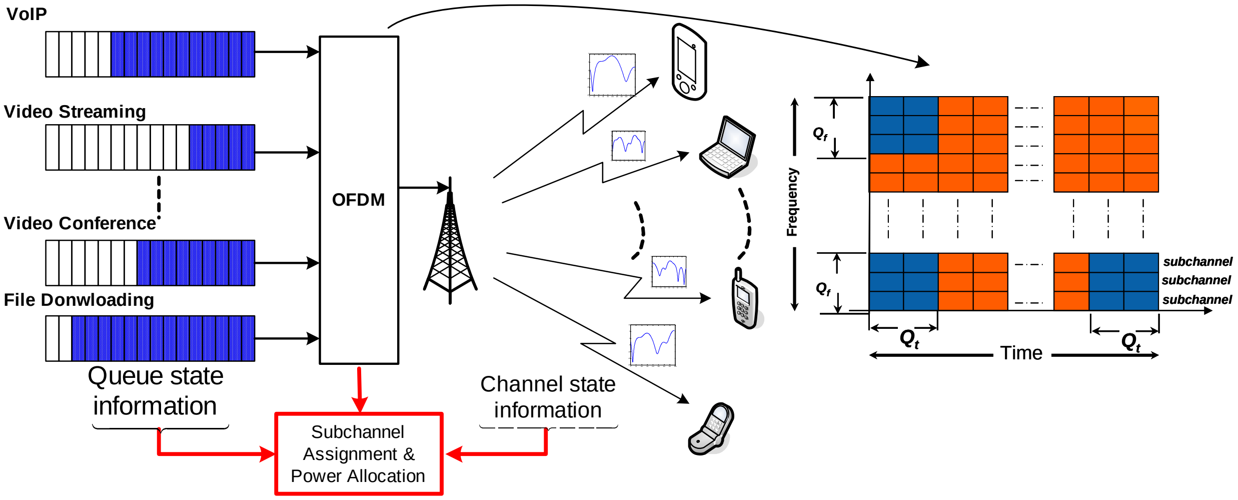


Fig. 5: Energy-efficient resource management in OFDMA

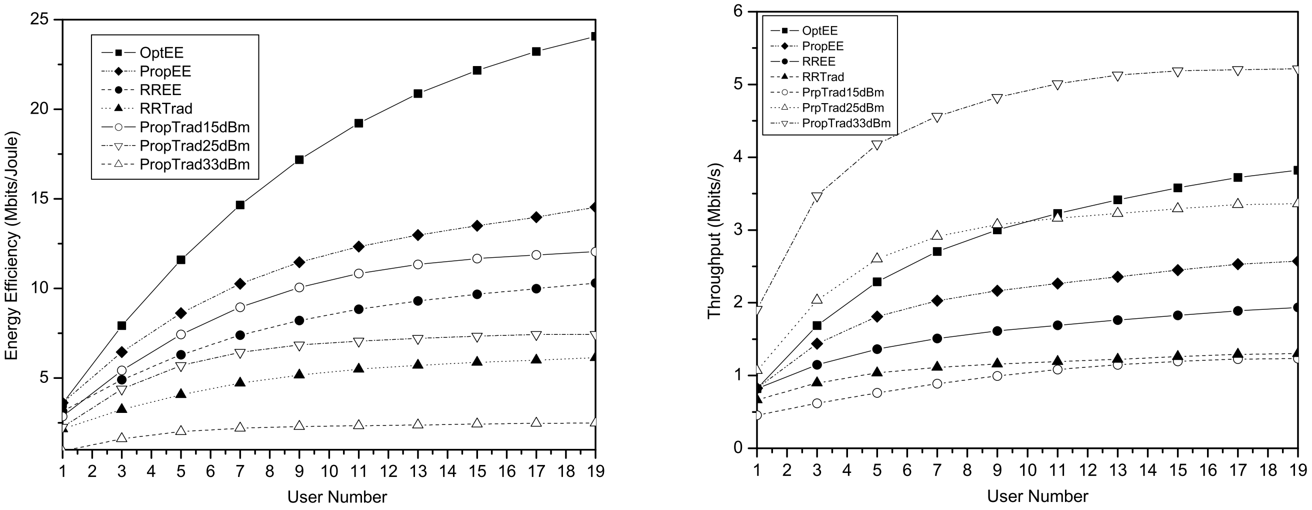
very important. As indicated in Section I, in order to save energy, components should be shut down when user is inactive and MAC schedules shutdown intervals according to system states, QoS requirements, and channel states. Coordination between users will help power management at the MAC layer to further reduce standby power consumption. For example, users can wake up precisely when they need to transmit or receive data.

The energy consumption of a Lucent WaveLAN IEEE 802.11 wireless network interface is measured in [45] to obtain knowledge of energy consumption behavior of actual wireless devices. In [46], different MAC protocols are investigated and their energy consumptions compared. From [46], collisions should be reduced as much as possible to save energy in contention based MAC protocols. Many wireless standards have integrated components to support energy-efficient communication capabilities. For example, IEEE 802.11 [47] recommends that a mobile be switched to sleep mode, while the base station buffers packets and periodically sends beacons with information about the buffered packets. The mobile decides whether to receive the buffered packets upon waking up based on the beacon information and informs the base station when it is ready. In this way, the mobile stays in sleep as long as possible and reduces power consumption. Similar schemes to extend sleep durations are supported in the IEEE 802.16e standard [10] and analyzed in [11]. When in sleep mode, mobiles decide whether to wake up or not after periodically checking whether there is downlink traffic or not. The sleep interval is increased exponentially when no arrival traffic is notified. In these MAC-layer schemes, fixed powers are used in transmit, receive, standby, and sleep mode. Asynchronous power management protocols with packet delay guarantee for mobile *ad hoc* network are developed in [48]. The system is optimized to allow users desiring energy-efficient transmission to spend as long time as possible in a low-power consumption sleep mode.

The circuit resource management is a generalized concept of duty cycling which was studied in some detail under the *Defense Advanced Research Projects Agency* (DARPA) Connectionless Networking program. Duty cycle is the proportion of time during which a component, device, or system is operated. The duty-cycles may be periodic or random depending on schedules and traffic [49]–[52]. In [49], a scheme is proposed to incorporate two-hop schedule exchange and to opportunistically turn off nodes. In addition, another scheme that combines opportunistic node turn-off and transmission backoff is also proposed to achieve high delivery capacity. Both of these schemes are effective in reducing average energy consumption and improving traffic delivery. It is also shown that exploitation of an additional feature of turning receivers off upon detection of unintentional traffic achieves near-optimal energy consumption and approaches the performance of perfect transmission scheduling.

B. *Time-domain resource management*

Most energy-efficient transmission techniques assume that a buffer always has data to transmit. This is not true in general. Due to random and bursty packet arrivals and varying PHY transmission states, buffers may be occupied or emptied, or may even overflow. Hence, to further enhance energy efficiency, traffic characteristics must be considered and scheduling is necessary to determine the transmission of each arriving packet while satisfying delay constraints. The problem is to minimize the energy used to transmit packets within a given period. From [53], packet transmission times and power levels can be varied to optimize energy efficiency.



(a) (b)

Fig. 6: Energy efficiency and throughput

As indicated earlier, it is desirable to transmit a packet over a longer period of time to conserve energy. Since all packets are delay constrained, the transmission time of any one packet cannot be arbitrarily long. With knowledge of arrival time of each packet, it is shown in [53] that optimal schedule is to have equal transmission times for each packet under feasibility constraint. A lazy scheduling that trades off delay for energy has been developed in [53]. In this scheduling, packets must be buffered. With a small buffer, it is shown that energy consumption can be significantly reduced as compared with a zero-buffer scheme. Based on this observation, transmission periods can be varied according to buffer states and the statistics of packet arrival process to save energy for practical applications where future packet arrival time is unknown. It has been demonstrated that lazy schedulers can achieve over 40% energy savings compared to a deterministic scheduler. Similar approaches are also proposed in [54]–[56].

In a TDMA network, the channel medium is shared through time division. Each user tends to extend their transmission time to save energy and contradicts the intention of energy savings of other users. Thus the allocation of time duration among all users is critical in determining network energy efficiency. Consider an energy-efficient variable-length TDMA scheme [57]. As the modulation order determines data rate and thus time for transmitting a certain amount of information, finding the optimal slot length for each user is thus equivalent to determining its corresponding constellation size. Therefore, the MAC layer and PHY layer should be jointly designed for overall energy efficiency. Consequently, the modulation orders of all users should be jointly optimized. A wireless network with central MAC is considered in [3]. The resource allocation scheme within the *access point* (AP) assigns time slots of the channel to all users and specifies transmission parameters of each user for energy-efficient communications. To make the resource management scheme applicable, the scheduling is partitioned into a design-phase and a run-time phase. In the design-time phase, energy-performance representation can be derived for each user to capture the relevant energy and performance tradeoffs. In the run-time phase, a fast greedy algorithm is used to tune the operating points to further improve energy efficiency.

C. Frequency-domain resource management

As indicated previously, while increasing transmission bandwidth always improves energy efficiency, the entire system bandwidth can not be allocated exclusively to one user in a multi-user system since this may hurt the energy efficiency of other users as well as that of the overall network. Hence, frequency-domain resource management is critical in determining overall network energy efficiency.

In OFDMA, the BS is in charge of subchannel assignment for both uplink and downlink communications based on channel states and service QoS requirements as shown in Fig. 5. Our initial research in [32] have investigated resource allocations in the uplink transmission of OFDMA systems both with and without fairness constraint. A throughput per Joule metric is considered for resource optimization. We have developed globally optimal subchannel assignment policies

TABLE II: Scheduling and Transmission Schemes

Legend	Scheduler	Modulation
OptEE	*energy-efficient* (EE) scheduler w/o fairness	EE transmission
RREE	round-robin	EE transmission
RRTrad	round-robin	2, 4, or 8-QAM
PropTrad	proportional fair	adaptive mod. w/ fixed transmit power
PropEE	EE scheduler w/ proportional fairness	EE transmission

that maximize the overall network energy efficiency. Figure 6(a) compares energy efficiency of different resource allocation schemes as shown in Table II and Figure 6(b) shows corresponding throughput comparisons. All users are subject to 33 dBm maximum transmit power constraint and the circuit power is assumed to be 100 mW. In the figure, we compare the energy-efficient schedule (PropEE) with the traditional proportionally fair schedule at 25 dBm transmit power (PropTrad25dBm) both with proportional fairness and link adaptation. We have observed that although the energy-efficient proportional schedule has approximately 20% less instantaneous throughput than traditional (proportionally fair) schedule, it can transmits 100% more data given a fixed amount of energy. Or equivalently, energy-efficient proportional schedule saves 50% energy. While energy-efficient scheduling can optimize the energy utilization, overall throughput is not optimized. Observing the performance of proportional scheduler with different values of transmit power in Figures 6(a) and 6(b), the throughput increases as the transmit power while the energy efficiency decreases. Energy efficiency and spectral efficiency do not necessarily agree and a tradeoff exists. Energy efficiency and throughput efficiency can be balanced according to user QoS demands and availability of battery power. While spectral efficiency can always be improved by increasing transmit power in an interference free environment, our further study shows that this does not hold in interference limited communication scenarios since increased transmit power also brings higher interference to the network. On the other hand, conservative energy-efficient communications reduce interference to other users and thus improve overall network spectral efficiency.

We have achieved globally optimal energy-efficient resource allocation for flat fading channels. For frequency-selective channels, modulation and power allocation depend on both the subchannel assignment and the state of each subchannel while the subchannel assignment at BS also depends on the modulation and power allocation of each user. Note that, resource allocation in frequency-selective channels is far from a trivial application of the traditional utility scheduling schemes [58]–[63] and is much more difficult in that the utility depends on rate vector instead of the overall rate.

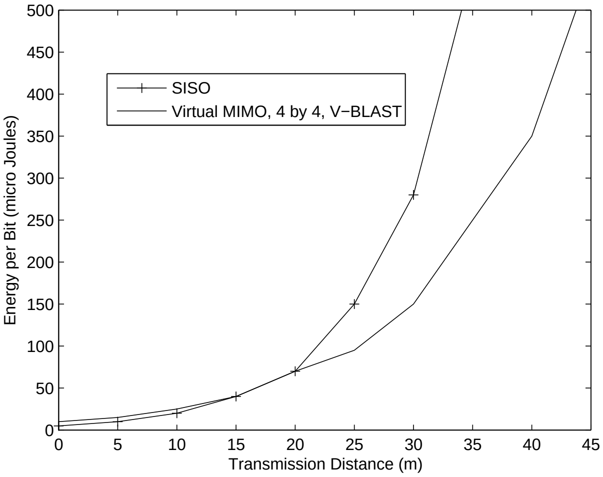


Fig. 7: Energy consumption transmitting one bit in 4×4 V-BLAST-based virtual MIMO and SISO with both optimized M-QAM modulation

D. Spatial-domain resource management

Since wireless is broadcast, transmission of one user will interfere with neighboring users and reduce their energy efficiency. However, users can gain in energy efficiency if cooperation among neighboring users is allowed. Hence, spatial-domain resource management is important to manage user behavior and to optimize overall network energy efficiency instead of that of individual one.

As discussed before, MIMO techniques can provide significant energy efficiency improvement. A network with cooperation among users is a virtual MIMO system, in that users themselves provide the spatial degrees of freedom, and can be constructed to enhance network energy efficiency from this point of view. On the other hand, cooperation requires signalling overhead and consumes additional energy. Cooperation based on inaccurate channel state information may also be harmful. Cooperation can also cause transmission delay that may impact throughput adversely and thus hurt energy efficiency. However, delay can be exploited for energy-efficient link adaptation, as extending transmission duration may improve energy efficiency. There has been some research in user cooperation for energy efficiency. It has been observed that significant energy savings can be achieved and the savings grow almost linearly with distance when either transmitter or receiver cooperation is allowed [39]. Furthermore, it is also observed that cooperation can even reduce delay within a certain transmission ranges. This is because cooperation enables on of higher order modulation to increase data transmission rate and reduces packet transmission time and delay. In [64], an energy-efficient virtual MIMO communication architecture based on V-BLAST receiver processing is proposed by assuming receiver cooperation. As shown in Figure 7, the proposed virtual MIMO architecture can offer significant energy savings over traditional SISO based wireless sensor networks.

From the Shannon capacity formula, the energy for reliable data transmission grows exponentially with distance, which is much faster than the linear relationship between energy and distance. Thus it is more energy-efficient to send data using several shorter intermediate hops than using a long hop, if the energy to compute the route is negligible [65]. Hence, relays are effective in saving energy. However, relay incurs transmission delay and energy consumption of relay nodes. Therefore, in some scenarios, it is advantageous to use long-hops [66]. Hence, the optimal selection of relay nodes should be a trade-off between source-node performance and relay cost to enhance overall network energy efficiency.

Most research assumes omni-directional antennas and since power attenuates rapidly with distance, a large portion of energy is wasted. Directional antennas can be used to save energy and reduce interference [67]. An energy-efficient routing and scheduling algorithm is thus designed in [67] to coordinate transmissions in *ad hoc* networks where each node has a single directional antenna.

E. Hybrid-domain resource management

In order to fully exploit network capability for energy efficiency, resource management across multiple domains should be designed as their performance affects each other.

A simple hybrid resource allocation example is the combination of TDMA and *frequency division multiple access* (FDMA). With pure TDMA, full bandwidth is allocated at each time slot, achieving the highest data rate and the shortest transmission period. Hence, circuit power consumption is minimized. However, with TDMA, more signalling overhead, e.g. synchronization, incurs additional power consumption as compared with FDMA. In a centralized network, non-ideal synchronization will cause overlap of packet transmission. In a distributed TDMA network, collisions will lead to packet reception failures. These also waste network energy. With pure FDMA, the bandwidth allocation is minimized achieving the lowest data rate. Thus maximal transmission time is required. Furthermore, all users will keep their radio on in FDMA and carrier frequency offsets in the oscillators and Doppler spread cause frequency domain overlap which make frequency synchronization critical. These result in the highest circuit power consumption. Hence, both time-domain and frequency-domain resources need to be managed jointly to obtain higher energy efficiency. A hybrid time and frequency domain multiple access scheme is presented in [30] for microsensor systems. In the system, time division is employed and the base station sends out sync packets to synchronize behaviors of all sensors. All sensors are turned on to receive the sync packets and consume energy. The frequency of sync packet receptions depends on bandwidth allocation that depends on FDMA policy. It is observed in [30] that smaller bandwidth allocation results in longer frame duration and thus less frequent receiver sync activity. With the increase of allocated bandwidth, sensors need to be turned on more frequently for synchronization and the receiver power starts to become a significant portion of overall network power consumption. Thus a tradeoff needs to be found between transmitter and receiver power consumptions by developing hybrid time and frequency domain resource management.

TABLE III: Energy consumption per FFT operation

	Non-scalable		Scalable	
FFT length	8-bit	16-bit	8-bit	16-bit
1024-point	1320 nJ	1448 nJ	575 nJ	1491 nJ
512-point	607 nJ	750 nJ	240 nJ	629 nJ
256-point	269 nJ	334 nJ	103 nJ	269 nJ
128-point	118 nJ	147 nJ	44 nJ	116 nJ

IV. IMPLEMENTATION ISSUES

In the past several years, many research groups have actively implemented energy-efficient communication techniques.

With energy-efficient communications, the system should assemble components that present a controllable tradeoff between performance and power consumption. Based on this flexibility, the system can adapt to dynamic environments and traffic conditions to avoid traditional worst-case communications and globally reduce power consumption. We have identified a set of parameters that influence the system-level energy efficiency and performance, i.e. modulation and coding scheme, transmit power, access policy, and so on. Using these parameters as control knobs, energy management policies are systematically derived at design-time and calibrated at run-time in [3] to adapt the system configuration to the actual user QoS requirements and environment parameters. By exploiting these knobs of actual RF components over a modified IEEE 802.11 MAC, system lifetime is shown to be increased by a factor of 2 to 5 over conventional techniques. Duty-cycling techniques and careful choice of various design parameters has led to the development of a very energy efficient sensor network radio [68].

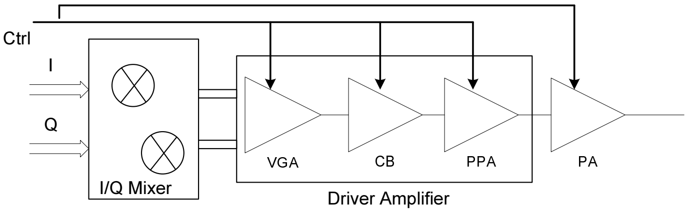


Fig. 8: Block diagram of the analog transmitter

Besides MAC layer implementations, there are also several efforts for PHY layer realizations. In [69], an OFDM transmitter design, shown in Figure 8, that effectively presents these characteristics is presented as well as its control strategy. The system consists of the following three stages: an *inphase and quadrature* (I/Q) direct-upconversion mixer, a driver amplifier and an external power amplifier. Both the driver amplifier and power amplifier are made flexible in terms of controlling output power, linearity, and DC power consumption. To optimally calibrate system parameters, a controller is designed to translate the high-level transmit power and linearity requirement in optimal circuit settings. The system-level energy management technique postulated in [70] is applied on the transmitter architecture and its control subsystem in [69]. Based on measurement carried out on the physical realization of the transmitter, the benefit of the aforementioned system-level energy management technique has been re-evaluated. It is shown that the proposed transmitter presents an energy-scalability up to 30%, which translate in average system-level energy efficiency improvement of up to 40%.

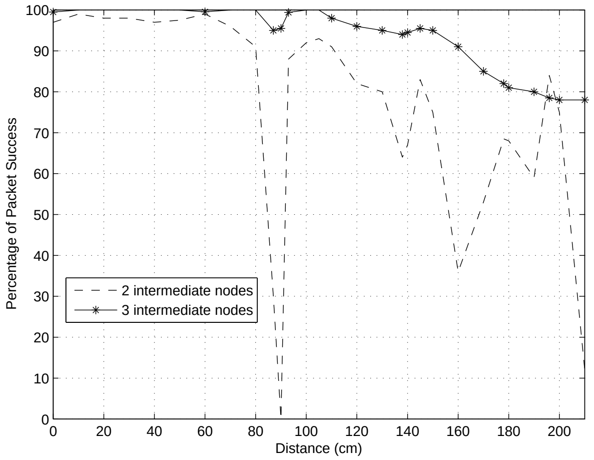


Fig. 9: Effect of forwarding

Rather than improvement of existing systems, there are also work at designing new system architectures to comprehensively enhance network energy efficiency, such as the PicoRadio project at Berkeley [65], [71] and the μAMPs project at MIT [72]. The PicoRadio project at Berkeley [65] designs an architecture that aims to provide flexibility for low-energy multi-hop communications and the architecture is implemented in ASIC, FPGA, and ARM platforms. We have known that it is more energy-efficient to send a bit using several short intermediate hops than using one longer hop and the most energy efficient routing policy is using infinite number of hops, each over the smallest possible distance. Besides, appropriate selection of intermediate hops can also improve link quality and thus increase the probability of transmission success to save retransmission energy. Figure 9, from [71], shows the advantages of using intermediate nodes for packet forwarding in PicoRadio. The percent of packet success is the ratio of times a packet reached its destination. The deep fades in the dashed line indicates nulls in the radio signal. The fade goes away, as shown by the solid line, when a third node is added in a more advantageous location and can forward the packet to the destination. Obviously, the number of intermediate hops is limited by how many nodes lie between nodes, but there are more factors to take into account, e.g. energy dissipation in transceiver processing and retransmission. In [65], the optimal number of hops is determined by finding the best energy trade off between transmission, retransmission, and overhead. The architecture consists of a parameterized and configurable physical layer to determine power control modes, modulation scheme, and bit rate for energy efficiency. This configurable architecture enables energy minimization opportunities in wireless networks to be efficiently realized in silicon. The MIT μAMPs project [72] focuses on architecture and circuit design techniques for energy efficient communications of wireless microsensor systems with lower transmission distances $(< 10m)$ and lower bit rates (typically $<$ kbs). The μAMPs-1 sensor node processor uses dynamic voltage scaling to minimize energy consumption for a given performance requirement. The radio transmit power adjusts to one of six levels, depending on the physical location of the target nodes. Power consumption of the node varies from 3.5mW in the deepest sleep state up to almost 2W. To enable energy-awareness of the *Fast Fourier Transform* (FFT) algorithm, its implementation includes tunable structures, such as memory size and variable bit precision, to handle a variety of scenarios effectively. The energy scalable FFT architecture was simulated in a 0.18 μm CMOS process at 1.5-V operation and the simulated energy dissipated is summarized in Table III from [72], which shows a definite advantage for a scalable architecture over a nonscalable architecture. The scalable architecture is more energy-efficient for all but the high quality point (1,024 point, 16-bit). At the high quality point, the scalable design has a disadvantage due to the overhead logic. The scalable FFT processor was also fabricated in a standard 0.18 μm CMOS process and standard ASIC flow to demonstrate these energy-scalable architectural techniques. At 1.5-V operation, when compared to a StrongARM SA-1100 implementation, the FFT processor shows over a 350X measured energy reduction. Since the μAMPs project focuses on short range communications with short packets, circuit components (frequency synthesizers, mixers, etc.), rather than the power amplifier, dominate power consumption. In order to reduce transmission start-up time, which is crucial in determining circuit power consumption, the energy-efficient transmitter uses a variable loop bandwidth method [73] for the phase-locked loop. Furthermore, similar to the PicoRadio project, energy efficiency in the μAMPs project is also enhanced through multi-hop routings and the energy-optimal number of hops is determined by both distance independent and dependent components.

V. CONCLUSIONS

We have described recent advances in energy-efficient wireless communications that exploit cross-layer design. We mainly focused on link-level transmission schemes and network/MAC layer resource management policies. Both theoretical analysis and implementation results are provided. Existing research has proved that optimized wireless communications can significantly reduce network power consumption. However, there is still huge margins across the entire protocol stack. To capitalize on the interdependencies of the different layers, advances in theory are required to determine the fundamental bounds on achievable energy efficiency. Correspondingly, research into practical realization and hardware implementations of energy-efficient protocols is also required.

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