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Advanced Energy Efficient Communication Techniques for Wireless Ad Hoc and Sensor Networks

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1. Introduction

Ad hoc and wireless sensor networks (WSNs) have recently attracted growing interest in the research and commercial community. Wireless devices are becoming smaller with lots of embedded computing capabilities. In addition, mobile computing, which is the ability to use computing capabilities even when being mobile, has also become the focus of very recent research efforts. The use of this ability has been greatly enhanced by wireless networking.

The key feature of mobile computing technologies is mobility/portability. However, as mobile devices are battery limited, energy efficient communication techniques have become of critical importance. Increased data transmission on the wireless interface results in more consumed energy, while local data storage and data processing might also incur significant energy costs. Consequently, it is very important for the modern wireless networks to reduce the energy consumption of the communication part in order to maintain high battery autonomy. The energy saving problem in wireless communication networks has attracted the interest of the researchers for many years now. Many approaches on various OSI layers have been proposed for energy efficiency, from the classical wakeup mode to energy efficient routing protocols and applications. Nevertheless, most of the research efforts are focused on the lower layers: Physical and MAC.

The objective of this chapter is to survey methods for the preservation of this limited resource - energy. Firstly, it presents a brief description of a simple energy consumption model for wireless communications in order to familiarize the reader with the major energy consumption causes. Afterwards, there are introduced two advanced energy efficient communication techniques: the opportunistic scheduling and the collaborative beamforming. Particularly, according to the first technique, channel fluctuations are exploited opportunistically (through time or multi-user diversity) in terms of minimizing energy consumption and transmitting in good channel conditions. On the other hand, the main idea of collaborative beamforming is grouping nodes to collaboratively send their shared data to the same destination in order to increase the cumulative transmission power and save energy. The basic principles of each technique are presented together with an analytical survey of literature's proposed schemes for the purposes energy consumption minimization. Finally, their advantages and disadvantages are also discussed.

2. Power consumption in wireless communications

This section makes a brief presentation of the basic energy consumption model for wireless communication devices and the typical power consumption values. A wireless device (e.g. ad hoc device, sensor node, etc) consumes energy for many operational functions (communication, processing, memory, etc). One of the most power expensive functions, which is of utmost importance and interest for a communications engineer, is data exchange, namely data communication. In order to focus on the wireless communication part, the total power consumption of a wireless module will be considered as the aggregation of the power consumed for communication (P_{com}) and the power consumed for other electronic functions (P_{electr}) and can be given by:

$$P_{tot}=P_{com}+P_{electr} \tag{1}$$

A realistic wireless communication module (Wang et al., 2006) can be shown in Fig. 1. This simplified module consists of a power supply (battery) that provides energy to device's circuits (radio circuits and other electronics' circuits). The radio or communication circuits are responsible for the communication of the device with the environment and thus for the data transmission or reception. They are consisted of the baseband digital circuits, the IF/RF circuits (responsible for the frequency conversion, modulation or demodulation, etc.), the RF amplifiers (power amplifier-PA for transmission and low noise amplifier-LNA for reception) and finally the switch that schedules when the module behaves as a transmitter and when as a receiver.

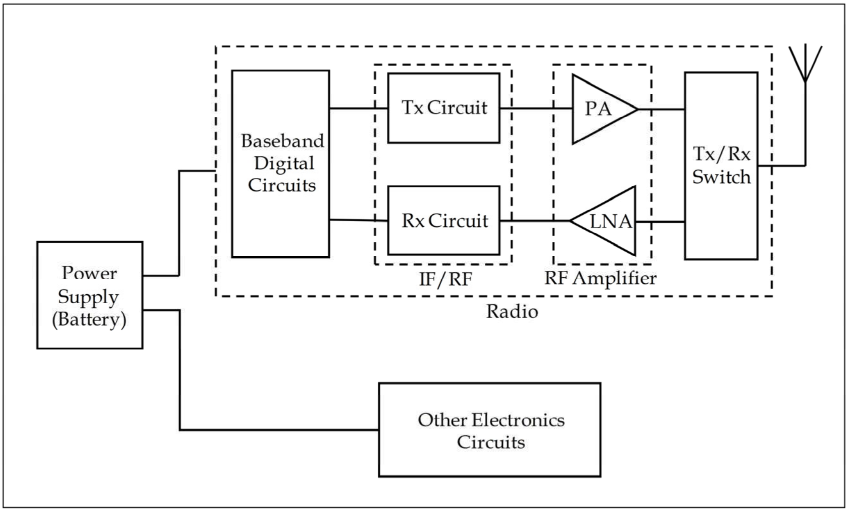

Fig. 1. A simple structure of wireless communication module

Since the focus of this chapter is on communication's energy consumption, the first term of (1) will be analyzed in the following. More specifically, the communication's power consumption consists of the power that is used for transmitting (P_T) and the power for receiving (P_R), as follows:

$$P_{com}= P_T + P_R \tag{2}$$

Based on the structure of communication module of Fig. 1 and assuming that the physical communication rate is constant, the total power consumption for transmitting and for receiving are given respectively by the following expressions:

$$P_T\,(g) = P_{TB} + P_{TRF} + P_A(g) = P_{T0} + P_A(g) \tag{3}$$

$$P_R = P_{RB} + P_{RRF} + P_L = P_{R0} \tag{4}$$

where P_{TB} /P_{RB}, P_{TRF} /P_{RRF} and $P_A(g)/P_L$ are the power consumption consumption in baseband circuits, in IF/RF circuits and in amplifiers during transmission and reception respectively and g is the channel gain of the wireless link (consists of path losses, shadowing and multipath phenomena/fading). The power consumption for receiving (P_{R0}) is considered constant since it is assumed that it does not depend on the transmission range and the link conditions. On the contrary, the power consumption for transmitting can be modeled in two parts, one constant that doesn't depend on the transmission range and the link conditions (P_{T0}) and the power consumed in the power amplifier ($P_A(g)$) that depends on the transmission requirements and the channel of the wireless link. It is interesting to refer some typical values of commercial RF modules (Wang et al., 2006). For ultra low power RF transceiver CC1000, we have P_{R0}=22.2mW and P_{T0}=15.9mW at 433MHz and for IEEE 802.15.4 compliant and ZigBee ready RF transceiver CC2420, we have P_{R0}=59.1mW and P_{T0}=26.5mW at 2.4GHz.

The RF output power of the transmitter's amplifier is given by:

$$P_{Tx}(g) = \eta \cdot P_A(g) \tag{5}$$

where η is the drain efficiency of the amplifier (Kazimierczuk, 2008), which depends on its' class (e.g. drain efficiency of Class B RF amplifier is ideally 78.5%). Consequently, the total power consumption for transmission can be given by:

$$P_T(g) = P_{T0} + P_{Tx}\,(g)/\eta \tag{6}$$

Moreover, in order to achieve the required signal level at the receiver (receiver's sensitivity) (P_{Rxmin}) for correct decoding, the transmission power consumption of the communication module for single-hop communication and for a given radio environment, is given by:

$$P_T(g) = P_{T0} + \frac{A \cdot P_{Rx\min}}{\eta \cdot g} \tag{7}$$

where A can be determined by the characteristics of the transmitting and receiving antennas.

Finally, considering the inherit multi-hop functionality of wireless ad hoc and sensor networks, it is useful to evaluate the power consumption model for a multi-hop network. It is assumed that the nodes that participate at the multi-hop transmission can decode and forward data having no amplifying capability and in all the hops, nodes have the same antenna receiving and transmitting diagrams. Thus, we can obtain the total multi-hop power consumption (for n hops) adding up the transmission and reception power of individual hops, considering identical received requirements (P_{Rxmin}) for each node, as follows:

$$P(n) = n\left(P_{R0} + P_{T0}\right) + \frac{A \cdot P_{Rx\min}}{\eta} \sum_{i=1}^{n} \frac{1}{g_i} \tag{8}$$

In rest of the chapter, we will focus on the contribution of the communication power consumption that was analyzed above and thus we can assume that this part is the dominant part comparing to the power consumption at the other electronics. In some specific applications that are using for example great processing power (e.g. video monitoring), the power consumption of the other electronics has major contribution but this is out of the scope of this chapter.

3. Energy efficient communication techniques

This section focuses on infrastructureless wireless ad hoc and sensor networks and it will extensively present some advanced energy efficient communication techniques. The concept of energy efficiency communications has been created by the attempts of engineers to optimize the communication's energy consumption. The general minimization problem (Cheng et al., 2011) that can be considered in energy efficient communications, is the following:

$$\begin{aligned} &\min \ \{Energy\ \ Consumption\} \\ &\text{s.t.} \quad Rate \text{ or } SNR_{receiver}\ constraint \\ &\qquad\ \ Delay\ constraint \end{aligned} \tag{9}$$

where $SNR_{receiver}$ is the signal to noise ratio at the receiver. In most cases, energy consumption is translated in the energy consumed for the transmission of a single bit. Considering the Shannon's theorem, the transmitted power for a AWGN channel can be given by:

$$P_{Tx} = \frac{\left(2^{R/W} - 1\right)N}{g} \tag{10}$$

where R is the channel capacity, W is the channel bandwidth, g is the channel gain and N is the noise power. Thus, in order to derive the transmitted energy per bit (in J/bit), the transmitted power must be multiplied by the transmission time of one bit ($1/R$) and it is expressed as follows:

$$E_C = E_{Tx} = \frac{P_{Tx}}{R} = \frac{\left(2^{R/W} - 1\right)N}{gR} \tag{11}$$

In the rest of this section, there will be discussed two energy efficient techniques highlighting their advantages and their critical issues. The first one is opportunistic scheduling communications, while the second one is the emerging collaborative beamforming technique. Both techniques can be employed for efficient energy usage of the battery-limited wireless devices with great results. The basic principles of these techniques will be analyzed and an analytical survey of the methods that have been proposed in the literature will be presented.

Finally, we note that in order to evaluate an energy efficient technique, a useful metric is the energy efficiency (ε) that can be described as the percentage of energy consumption gain, comparing the energy consumption with the presence ($E_{C,W/-}$) of the corresponding technique and its absence ($E_{C,W/O}$) and can be expressed by:

$$\varepsilon = 1 - \frac{E_{C,W/-}}{E_{C,W/O}} \cdot 100\% \qquad (12)$$

3.1 Opportunistic scheduling

In wireless networks, the random fading environment varies channel conditions with time and from user to user. Although, channel fluctuations are traditionally treated as a source of unreliability, according to recent researches they can be opportunistically exploited when and where the channel is strong, by scheduling data transmissions. Opportunistic scheduling (Zhang et al., 2007; Gulpinar et al., 2011) commonly referred to opportunistically transmitting (more) data when the channel between the sender (e.g. user) and receiver (e.g. base station - BS) is in a "good" state and no (or less) data when the channel is in a "bad" state. This technique increases system throughput and reduces the total energy consumption.

More specifically, there are two main categories of opportunistic transmission scheduling. The first one exploits the time diversity of an individual link by adapting the transmissions to the time-varying channel conditions. In other words the sender transmits at higher rates or just transmits when the channel conditions are better, while he transmits at lower rates or postpones transmission when the channel conditions are worse (see Fig. 2). The second one exploits the multi-user diversity, which jointly exploits the time and spatial inhomogeneity of channels to schedule transmissions. In a multi-user network, like the one depicted in Fig. 3, a BS may receives data originated from multiple users. Scheduling their transmissions and selecting instantaneously an "on-peak" user with the best channel condition improves system performance.

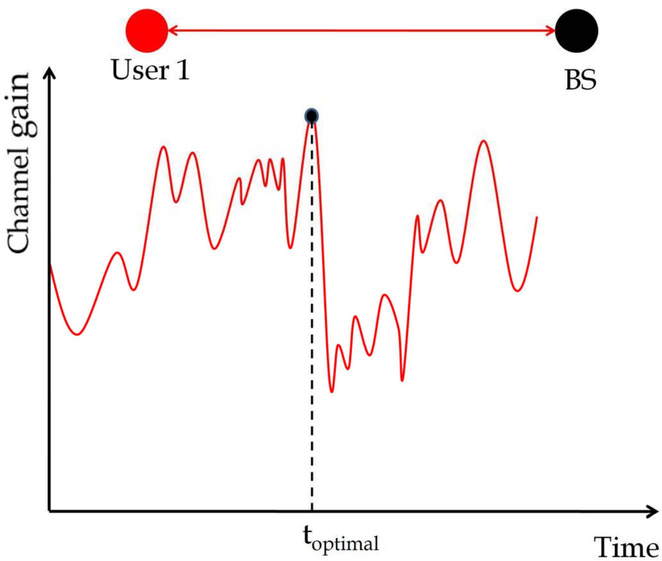

Fig. 2. Time diversity

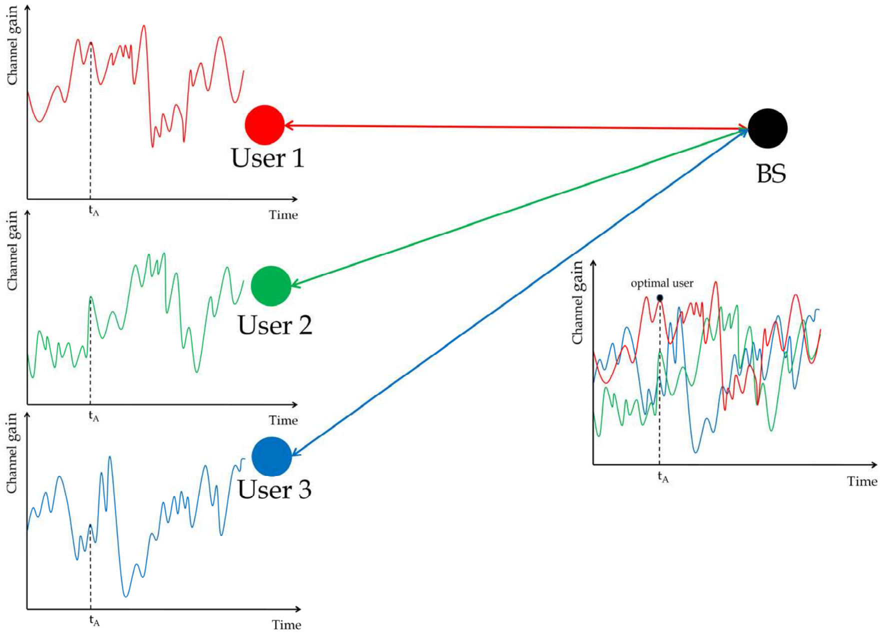

Fig. 3. Multi-user diversity

The basic assumption of opportunistic scheduling is the knowledge of channel state information (CSI). Through a feedback channel, the transmission scheduler learns perfectly the state of the channel between each sender and each receiver at the beginning of every time slot. Its' scheduling decisions are usually based on all past and current states of the channel, but none of the future channel conditions. This is commonly referred to as causal or full CSI. This can be also referred as online scheduling to differentiate from the technique where the scheduler learns all future channel states at the beginning of the time horizon and can be called offline or non-causal scheduling. Nevertheless, the full CSI is an ideal assumption and in many practical cases cannot be implemented. Thus, many researchers use the partial CSI, a more realistic assumption where the various imperfections on CSI acquisition are explicitly taken into account.

3.1.1 Time diversity scheduling

This subsection presents how the time diversity provides energy efficiency. In order to formulate the energy efficient time diversity scheduling, there are two main approaches. Based on the relation of energy consumption in (11) with the channel gain and the rate (channel capacity), which can be depicted in Fig. 4 through a set of curves, one can reduce energy consumption simply if he schedules data transmissions when the channel condition exceeds a specific channel gain threshold or if he adapts transmission rates depending on current channel condition. In the following, we briefly discuss research efforts on energy efficient time diversity scheduling.

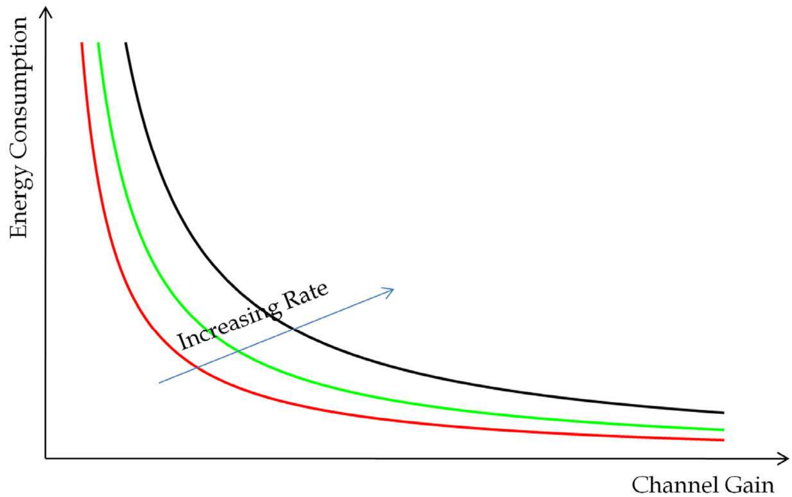

Fig. 4. Set of energy consumption-channel gain curves for different rates

A distributed cooperative rate adaptation scheme in order to achieve energy efficiency in wireless ad hoc networks by exploiting time diversity in opportunistic transmission, is proposed in (Zhang et al., 2007). Since it is hard to optimize the overall system performance without cooperation among nodes, the authors in (Zhang et al., 2007) prompt the "cooperative and opportunistic transmission" concept in fading environments. More specifically, the proposed scheme consists of information exchange and rate selection which can be fulfilled through node cooperation. Each node obtains relevant information on all the links in its maximum interference range by information exchange. This information includes the required channel time for satisfying the traffic requirements and the corresponding power consumption under all possible rates on the link. After that, all nodes calculate the most energy-efficient setting of rates for all the links in their interference range, using a rate selection algorithm. Then, each node consults the neighboring nodes about the feasibility (the probability that quality of service-QoS requirements can be fulfilled) of this new rate setting. The above procedure is repeated until it converges and the rate become feasible. Finally, the rate setting is changed and it can reduce energy consumption. This rate-adaptive power minimization problem is NP-complete and thus the authors decompose the problem into sub-problems for each node and seek a heuristic solution for the rate selection algorithm.

In (Phan & Kim, 2007), the authors propose an energy-efficient scheme for WSNs over fading wireless channels. The proposed scheme takes an opportunistic approach where transmissions are initiated whenever it is possible and only under good channel conditions. In particular, it uses the combination of two parts of MAC protocol, a binary decision based transmission and a channel-aware backoff adjustment. The binary decision based transmission scheme determines when to initiate transmission according to the current channel conditions. Particularly, transmission starts only when the channel quality exceeds a specified threshold. This technique avoids whenever possible the unsuccessful transmissions causing a waste of energy. The optimal threshold for successful transmission obtained using the Markov decision process formulation and computed with dynamic programming techniques. Furthermore, the channel-aware backoff adjustment algorithm favors the sensor nodes that have better channel conditions. A smaller contention window is assigned to those nodes in order to access the channel faster, while a relatively larger one is given for the opposite cases. For simulation purposes, these transmission algorithms are used in the IEEE 802.11 distributed coordination function standard with some necessary modifications and the results show that the proposed scheme improves the energy efficiency up to 70% compared with the plain IEEE 802.11, while the throughput results are comparable.

The authors in (Chakraborty et al., 2006) introduce an energy minimization scheme that schedules transmission by exploiting the movement history of wireless mobile nodes. According to this scheme, the communication may be postponed until a tolerable delay, so as to come across with smaller path loss values. Particularly, in order to save energy in wireless communication, they take advantage of the fact that the reduction in physical distance between two communicating nodes often leads to reduction in energy consumption. In the single hop communication case, this is obvious since transmission power is proportional to the square of the distance (under line of sight-LoS condition) between communicating nodes. Nevertheless, in the multi-hop case, the decrease in physical distance doesn't always imply decrease in network distance. There are some other important factors like the network's state and density of the nodes in the network. However, the lengths of the individual hops are expected to be smaller and in a not very sparse network, reduction in physical distance between two nodes it is likely to save energy.

More specifically, this work considers the problem of predicting when two nodes will move closer to each other. If it is predicted that a mobile node will move closer to the target, communication can be postponed until the future time subject to an application imposed deadline. Once a node decides to postpone the communication, the next problem is to decide when to communicate within an allowable delay. This problem is analogous to the well known *secretary problem* in common optimal stopping theory (Ferguson, 2006). Secretary problem is a selection problem in which one must make an irrevocable choice from a number of applicants, whose values are revealed only sequentially. The solution of that problem is called the “37% rule”. According to this rule, the first 37% of the candidates are just evaluated, but not accepted. Then, the candidate whose relative rank is the first among the candidates seen so far is chosen. Based on that, the authors proposed an optimal policy that consists of a simple and efficient heuristic, the least distance (LD). They assume that have already seen the first 37% or more of the candidates as the location history and so the node communicates at the first chance when its distance of the target is less than or equal to the least seen so far. Therefore, in each timeslot the node checks if current distance is less than the minimum so far until the delay threshold in order to schedule transmissions.

Low-complexity and near-optimal policies for delay-constrained scheduling problem for point to point communication is considered in (Lee & Jindal, 2009). This work studies the considers the problem of transmitting B bits over T time slots, where the channel fades independently from slot to slot. The transmission scheduler determines how many bits to transmit depending on the current channel quality and the number of unserved bits remaining. The proposed scheme gives insight into the optimal balance between opportunism (channel-awareness) and deadline-awareness in a delay-limited setting and it can be used to model deterministic traffic in multimedia transmission when there are hard deadlines.

Especially, the proposed scheduler determines the number of bits to serve at each time slot, so as to minimize the expected energy and serve all the bits until the deadline T. It takes into account a combination of parameters: the remaining bits, the number of remaining slots, the current channel state, and a threshold channel level. If the current channel quality is equal to the threshold, then a fraction of the remaining bits are transmitted. If the channel quality is better or worse than the threshold then additional or fewer bits are transmitted. Consequently, the scheduler behaves very opportunistically when the current time slot is far away from the deadline and less opportunistically as the deadline approaches. The optimization problem can be formulated sequentially via dynamic programming. Due to the difficulty to obtain an analytical form of the optimal scheduler the authors make some relaxations and propose suboptimal algorithms. Additionally, the authors consider the case when the number of bits to transmit is small. In that case, the transmission of the entire packet at once may be wanted due to the potential overhead of multiple slot transmission.

Finally, considering that opportunistic scheduling asks for channel awareness, another important issue that must not be ignored is the cost of channel state acquisition. The authors in (Li & Neely, 2010) consider scheduling algorithms for energy and throughput optimality. They take into account a more realistic assumption that channel acquisition incurs power overhead and they propose a channel acquisition algorithm that dynamically acquires channel states to stabilize a wireless downlink. Due to the fact that it may be adequate and more energy efficient to transmit data with no CSI in low traffic rate cases, the authors propose a dynamic scheduling algorithm, which accomplishes data transmission with or without CSI, using queue backlog and channel statistics. Simulations verify that the algorithm efficiently adapts between channel-aware and channel-blind modes for various system parameters, including different values of channel probing power, different transmission power and different data rates.

3.1.2 Multi-user diversity scheduling

Due to the presence of many users, with independent fades, in wireless communication networks, there is a high probability that one (or some) of the users will have good channel(s) at any one time. By allowing only that user(s) to transmit, the shared channel is used most efficiently and the total system efficiency is maximized. The greater the number of users, the better tends to be the good channel(s), and the multi-user diversity gain is greater. Similarly with the observations about time diversity scheduling presented above, the main approaches that can formulate energy efficient multi-user diversity are inspired from the nature of energy consumption's function in (11). Fig. 5 shows the set of energy consumption-rate curves for different instantaneous channel gain representing the channel conditions of different users that aims at communication with the same node. Consequently, one approach in order to reduce energy consumption falls to the selection of the best user or the group of best users that will become active users (representatives), in terms of channel condition and they will be scheduled to data transmission considering some specified constraints (e.g. rate constraints). The critical issue here is the strategy that specifies the active users, which may be for example a threshold policy as in time diversity scheduling. Moreover, a multi-user diversity scheduler should guarantee fairness among the users' communication and not sacrifice it in order to result more system efficiency. The rest of this subsection presents research publications and proposed approaches on this energy efficient technique.

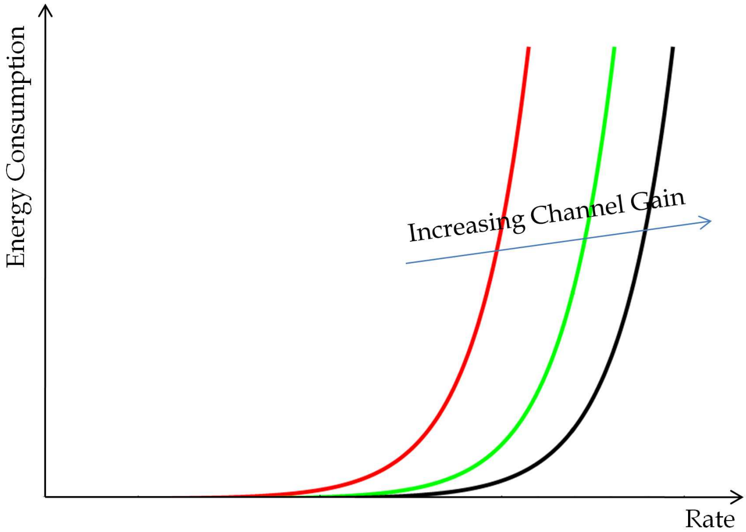

Fig. 5. Set of energy consumption-rate curves for different users (channel gains)

In (Bhorkar et al., 2006), the authors discuss energy optimal opportunistic control strategies for a multi-user TDMA (time division multiple access) network subject to minimum rate constraints. Particularly, they consider a multi-user TDMA system where base station has the role of centralized scheduler. It is assumed that time is divided into slots of equal duration, the channel is suffering from slow fading and the scheduler has perfect CSI for all wireless links. Moreover, the scheduler determines at any given timeslot the unique user who can transmit and its transmission power considering a specific rate constraint. Their method is to opportunistically schedule the user with the best channel condition such that rate is guaranteed and temporal fairness are achieved and average transmission power is minimized.

The authors propose a joint minimization problem of average transmission power subject to average rate constraints. Using Lagrangian method and a stochastic approximation based online algorithm to estimate the necessary parameters, they obtain the optimal policy that selects which user to transmit and with what power. Despite the energy efficiency that can be achieved through multi-diversity opportunistic scheduling, an issue that must always be taken under consideration is fairness among users. Thus, an additional long term fairness constraint with time average fraction of slots allocated to each user is considered. This constraint guarantees average proportional time share and specifically that each user has average access to certain number of time slots. Since considering only long term fairness has problems in some case, the authors also discuss a short term fair scheduler and devise a heuristic based algorithm. Their results show that as expected due to multi-user diversity when the number of users increases, the gain obtained from the proposed power scheme increases.

The work in (Hwang et al., 2009) proposes a method that reduces transmission power consumption of carrier-sense multiple-access (CSMA) based wireless local area networks (WLANs) by utilizing multi-user diversity and power control. According to this scheme, a terminal sends a packet at a slot if the terminal's SNR is above a specified threshold associated with the slot. Multi-user diversity is attained by using the opportunistic *p*-persistent CSMA (O*p*CSMA) scheme. In a simple *p*CSMA system, each user accesses the wireless medium with probability *p*, independently from the value of the corresponding SNR. On the contrary, in the O*p*CSMA system, each user maintains the same access probability by using a specific random variable defined by the corresponding SNR, exploiting the multi-user diversity. In particular, a user accesses the channel only if its SNR exceeds a predetermined threshold given by a specific formula (related with the inverse *cdf* of SNR) during the specific slot. This threshold's values decrease as time advances and thus this method makes the user with the largest SNR access the shared medium earlier than the others and transmit with less power.

In order to evaluate power efficiency, the authors use the expected sum-power metric, which is the expectation of the sum of transmitted power per packet of all users and represents the aggregate power consumption of an entire random-access network. Thus, the expected sum-power depends on the power control policy and the number of transmitting users per transmission opportunity. So as to reduce the expected sum power, this work combines the truncated channel inversion power control method with O*p*CSMA, applying the described threshold policy. The authors consider the infinite-user model and the simulation results show that the proposed scheme saves substantial energy compared to the conventional *p*CSMA, while maintaining the same throughput. Also, the proposed scheme was tested in an IEEE 802.11 WLAN and the results shown significant power saving as well as long-term fairness. Finally, the authors discuss some possible problems of the proposed scheme, like short-term fairness problems that may cause a large delay jitter (something undesirable for real-time applications). Additionally, they note that the transmission power control may hamper the operation of CSMA because it can deteriorate the hidden-node problem. After these problems are solved, the O*p*CSMA should be a highly effective protocol for wireless networks.

An opportunistic transmission scheme for the type-based multiple access system, which selects a set of sensors to transmit in order to provide energy efficiency is proposed in (Jeon et al., 2010). The discussed problem considers an unknown target to be detected and sensors that have statistically and temporally independent and identically distributed observations on this target and transmit them to a fusion center. The authors' goal is to minimize average power consumed by the sensors in order to achieve a detection error performance constraint. Thus, they propose a channel-aware opportunistic type-based multiple access scheme over a fading channel, exploiting the multi-user diversity for large WSNs for better energy efficiency, where all sensors do not need to be activated. Due to the multi-user diversity in WSNs, the authors allow the sensors experiencing higher channel gains than a given threshold (broadcasted by the fusion center) to participate in type-based multiple access and transmit data at their controlled power levels in a time-division duplexing manner. This set of sensor nodes (activated sensors) requires smaller amount of total energy consumed for reporting their observations reliably to the fusion center, and thus the lifetime of WSNs can be prolonged.

In particular, the authors formulate an optimization problem to minimize the average power consumed by the activated sensors while satisfying a given detection error performance. To solve this problem they first determine a power control policy to maximize an error exponent of the detection error performance and find a threshold to minimize the average power consumed by the activated sensors. The evaluations of the proposed scheme show that smaller number of sensors and reduced total energy are required, for the same detection performance in the low SNR regime, comparing with a random selection scheme, where nodes are activated regardless of their communication channel qualities.

Finally, the work in (Yoon et al., 2011) discusses another very important issue that arises when a scheme exploits multi-user diversity, the fundamental tradeoff between energy saving and throughput. Specifically, the performance gain from the multi-user diversity and the energy consumption for the channel feedback should be balanced. Thus, the authors propose an energy-efficient opportunistic scheduling scheme that goals to improve energy efficiency under the constraint of fair resource allocation by controlling the number of users that feedback their channel conditions to a BS. This can be achieved by combining opportunistic scheduling with energy-efficient sleep/awake scheduling.

In particular, this work considers a time-slotted system with a single frequency downlink channel that is consisted of N low mobile users and a single BS. At each time slot, the BS broadcasts a pilot signal and then n out of N users respond of their received SNRs to the BS. The users that report their channel statuses are referred as non-sleeping, and the others as sleeping. Then the BS chooses a single user (active user), to transmit/receive at this time slot. The other non-sleeping users are idle and deactivate their transceivers so as to save energy, similar with the sleeping users. In order to formulate the optimization problem, the authors consider the energy efficiency in bits per energy unit, given by the ratio of the expected throughput to expected energy consumption for a given set of non-sleeping users. Their objective is to maximize the average efficiency under the constraint of fair resource allocation which expressed as the time average of active users.

The authors first consider a network where each user has an identical mean SNR. Then, they express the energy efficiency in relation with the non-sleeping users and the initial problem simply becomes finding an optimal number of non-sleeping users that maximizes average efficiency. This is a quasi-convex integer problem that can be solved through the method of integer constraint relaxation on non-sleeping users. After that, they consider a more general network where users could have different channel statistics (different mean SNRs). Since it is hard to obtain an optimal solution due to complexity, there are proposed two heuristic approximations of the considered problem: one that uses the average mean SNR and another that classifies users into several groups according to similar mean SNRs. The performance of energy-efficient opportunistic scheduling scheme shows that it enables the network lifetime to be prolonged significantly at the cost of a slight degradation in the system throughput.

3.2 Collaborative beamforming

This subsection discusses the concept of collaborative beamforming in order to improve the energy efficiency and the transmission range of wireless networks. Specifically, the basic principles of collaborative beamforming are presented in the following, together with a brief analysis on the research efforts and the energy performance of this technique. Moreover, the critical issues of this technique are considered.

3.2.1 Principles of collaborative beamforming

Beamforming is a technique that can handle the problem of signal fluctuations at the receiver caused by several phenomena such as path loss, shadowing, and multipath fading. It is used for directional signal transmission or reception and it relies on the artificially creation of multipath fading by equipping the transmitter with multiple antennas and by sending the same signal from each antenna. Nevertheless, battery-limited devices in wireless ad hoc and sensor networks are likely to be equipped with a single antenna and so they cannot use beamforming. A solution to this problem is nearby users to cooperate with each other such that by sharing their transmission data and then synchronously transmit the compound data to the destination receiver. In essence, a set of distributed wireless nodes organize themselves as a virtual antenna array (see Fig. 6) and produce a desired beam pattern. Such beamforming is often referred to as a collaborative (or distributed) beamforming, because all the nodes that are grouped together collaboratively send their shared messages to the same destination (Ochiai et al., 2005; Ochiai & Imai, 2009). The term distributed beamforming is frequently used in the general case of wireless networks and the term collaborative beamforming is more usually used in WSNs. Nevertheless, there are some main technical challenges when implementing collaborative beamforming. The most important are the feasibility of precise phase synchronization between the collaborative nodes in order to produce the optimal output, the accurate channel estimation and the efficient sharing of messages among the nodes.

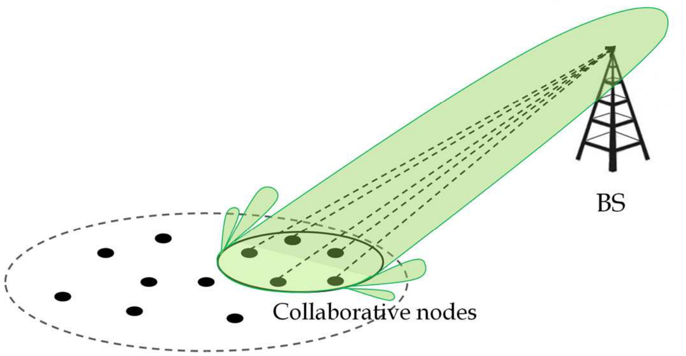

Fig. 6. Collaborative beamforming example in a WSN

Collaborative beamforming may be adopted in modern wireless ad hoc and sensor networks for the reasons below (Feng et al., 2009):

1. The black-out spots in the networks are minimized, which means that the transmission energy of the individual nodes is balanced and saved over multiple transmitters. This prevents some of the nodes from draining of energy much faster than the others (for example near sink nodes in WSNs).
2. It allows the signals to travel farther and reach a receiver too far for an individual transmitter (beyond its' range).
3. Data security is substantially improved. Beamforming reduces or completely eliminates signals to undesired directions.

Collaborative beamforming can be achieved by manipulating the initial phase of synchronized transmitting signals with identical message. Thus, all the nodes must be phase synchronized. This can be achieved by appropriately setting the initial phase of the transmitting signal of each user. Two possible scenarios can be used (Ochiai et al., 2005): closed-loop and open-loop scenario. In the first one, each node independently synchronizes itself to a beacon sent from the destination node adjusting its initial phase. Hence, the beam is formed in the direction of arrival of the beacon. In contrast, the open-loop scenario considers that all nodes within a group or a cluster acquire their relative locations from a beacon of a nearby reference point, the master node or the cluster head. In this case, the beam is steered toward an arbitrary direction.

In most of the literature's schemes that consider collaborative beamforming, there are made some identical assumptions. At first, each sensor node is equipped with an ideal isotropic antenna. Moreover, all nodes transmit with identical energies, and the path losses of all nodes are also identical with the absence of signal reflection and scattering. Also, all nodes are sufficiently separated such that mutual coupling effects are negligible and they are perfectly synchronized. The above are some general assumptions that are not always strictly followed.

Furthermore, a very important issue is the effects of the locations of distributed collaborative nodes in the derived beam pattern, which is discussed in (Ochiai et al., 2005; Ochiai & Imai, 2009). The authors consider many location distributions, but the most reasonable when someone deal with wireless ad hoc sensor networks, is that distributed antenna nodes are located randomly by nature. Therefore, the beam patterns of these random arrays are determined by particular realizations of randomly chosen node locations. As it is shown, if the sensors are randomly distributed and fully synchronized, the resulting beam pattern formed by these sensors has a nice sharp mainlobe and low sidelobes, with high probability.

3.2.2 Energy efficiency through collaborative beamforming

Collaborative beamforming is a signal transmission technique that can prolong the lifetime of a wireless network. Improving directivity of transmitted signals in order to be stronger at the receiver, it can save transmission energy. Each transmitter can individually save energy using lower power, since the energy consumption is spread over multiple transmitters. Particularly, if N distributed nodes are considered that transmit the same signal, each at power P, all transmissions add up coherently at the destination. As a result, the power of the received signal at the destination is proportional to N^2P. Thus, this technique leads to a N^2 gain at the received SNR, with only a N factor increment in total transmit power. Alternatively, we can say that the transmission range can be increased by N times farther and each node can reduce its transmit power to P/N, gaining a factor of N in power efficiency. Consequently, collaborative beamforming can achieve high energy efficiency.

Specifically, consider N distributed nodes, let E_{single} be the energy that a single node needs to transmit one bit to the destination and D be the amount of the data to be transmitted. In order to achieve efficiency, the transmitters have to coordinate their phases with high accuracy. Since, this is not always absolutely possible (allowing some tolerance in phase differences), collaborative beamforming is characterized of an efficiency (e) factor that is defined as the ratio of achieved signal strength and the highest possible signal strength. Consequently, using collaborative beamforming, each transmitter needs to only use $E_{single}/(N \cdot e)$ energy for sending one bit and that leads to the energy saving E_{saving} for each transmitter.

Moreover, collaborative beamforming can be divided into two stages: preparation and operation. At the pre-beamforming preparation stage all the necessary functionalities of synchronization and data sharing are taking place. During the operation stage all the collaborative nodes transmit their data simultaneously to the same destination. In order to formulate the total energy profit of collaborative beamforming, one must take into account the additional energy consumed by the data sharing and synchronization procedures that is referred as energy overhead $E_{overhead}$. Considering the above, the total energy profit for each node using collaborative beamforming is given by:

$$E_{total} = E_{saving} - E_{overhead} = E_{single} \cdot D \cdot \left(1 - \frac{1}{N \cdot e}\right) - E_{overhead} \quad (13)$$

Fig. 7 represents how the number of collaborative nodes affects energy saving of each node. Regarding the $E_{overhead}$, it depends on many technological constraints and cannot be simply represented.

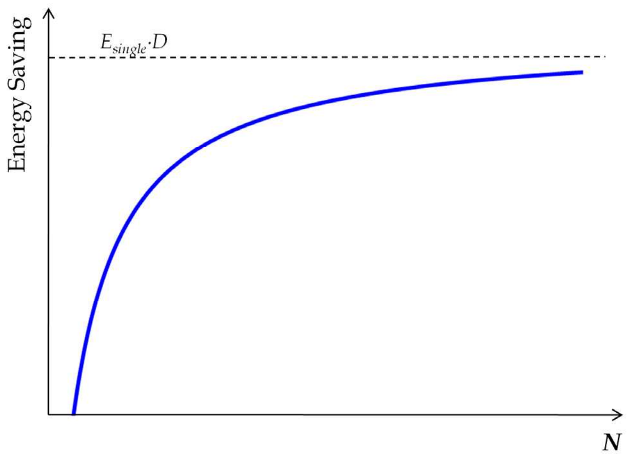

Fig. 7. Energy saving of each node using collaborative beamforming.

Several studies can be found in the literature that tackle the problem of collaborative beamforming and particularly the utilization of this technique in terms of reducing the energy consumption in a wireless networks. This technique is widely considered for WSNs, but the principles are the same for all the wireless network technologies. The rest of this subsection aims at quoting the most representative proposed techniques that deal with this problem.

The authors in (Feng et al., 2009) investigate the energy gain attained by using collaborative beamforming based on two critical factors, the number of collaborative nodes and the total size of data needed to transmit. In particular, in order to achieve beamforming's efficiency, all phases among the participating nodes must be proper coordinated with high accuracy. This requires communication among the nodes and consumes energy. Accuracy is measured by the wireless carrier's frequency and for example a π/6 accuracy of a 900 MHz carrier implies that the transmitters' clocks must be synchronized within 0.1 ns with a maximum location error of 2.8 cm. This phase synchronization can be achieved using an iterative algorithm for communication among nodes. Ideally, the phase difference must be zero for waves arriving at the destination to achieve *100%* efficiency (e) and the algorithm converges in several iterations something that increases the energy consumption for synchronization.

A tradeoff among efficiency and maximum phase difference is proposed in this work. Particularly, if the transmitters are allowed to have phase differences, the efficiency may be lower but convergence will be faster. For example, at a maximum phase difference π/6 the efficiency is *95%*, while at π/3 is almost *70%*. Consequently, by relaxing the convergence requirement, the transmitters can determine their phases faster and save energy in pre-beamforming preparation. Even for phase differences greater than zero, collaborative beamforming can still increase the received signal strength.

Moreover, in order the beamforming technique to save energy, the total profit of (13) must be greater than zero. These leads the authors to determine the minimum size of data $D_{\min}$ to be transmitted in order to balance the preparation overhead when the total number of nodes is given, as follows:

$$D > D_{\min} = \frac{E_{overhead}}{E_{single} \cdot \left(1 - \frac{1}{N \cdot e}\right)} \tag{14}$$

The simulation results verify that for a fixed number of transmitters, higher efficiency requires more iteration in pre-beamforming preparation and a larger minimum size of data to compensate this energy overhead.

Considering that for better performance, the nodes with small phase differences are always used, these nodes will exhaust their energy much faster than the others. This may cause coverage holes in WSNs, which referred to areas that are not monitored because the corresponding sensors run out of energy. To avoid this, a scheduling scheme that selects the transmitters in each round is necessary in order to balance the remaining energy over the entire network. A scheduling algorithm for nodes participating in collaborative beamforming is proposed in (Feng et al., 2010a). This algorithm is called energy and phase (EP) and selects the transmitters in each round in order to prolong network lifetime. Three rules are used in order to implement this selection: the remaining energy in all nodes need to be balanced, the signal gain at the receiver need to exceed a minimum level and the amount of data transmitted need to be maximized.

Especially, to prevent the nodes with low remaining energy from being energy-exhausted, the nodes with higher remaining energy should be selected first. Also, since smaller phase differences provide larger beamforming gain, the proposed scheduler selects nodes by giving higher priorities to smaller phase differences relative to a reference phase at the receiver. Thus, for each round, the authors sort and select nodes one by one based on their priorities (a specific product considering remaining energy and phase difference), to minimize wasted energy. After one node is selected, the signal gain at the receiver is computed. If it is greater or equal than the minimum required, the currently selected nodes are assigned to transmit for this round. This transmission schedule can be computed offline and broadcasted to all nodes. Finally, it can achieve 60% more beamforming transmissions than a phase partition algorithm, which divides transmitters into several groups based on their phases without considering the remaining energy in each node and the signal strength at the receiver.

In (Feng et al., 2010b), the authors discuss how data sharing affects the network lifetime and collaborative beamforming's energy performance. Data sharing is necessary, since the information collected by nodes at different locations may not be the same. It requires communication among collaborative nodes, which consumes energy and shortens the lifetime of the network. Consequently, this energy abates the energy saved by beamforming. This work proposes a procedure for data sharing and examines the energy that consumes. Specifically, the considered nodes are divides into groups and each collaborative beamforming transmission is assigned to one group at a time. The groups transmit to the base station in turns using TDMA. Also, nodes are assumed to be synchronized. There are four types of nodes in each round of sensing and transmission: beamforming transmitters, a master node, sensing nodes, and the other nodes that don't belong to the previous categories. Among all transmitters in each group, the one with the highest remaining energy considered as the master node. He gathers the data from all sensing nodes, aggregates and compresses them and finally multicasts the result data to the other transmitters. The simulation results show that collaborative beamforming is energy-efficient, when the sensor nodes are deployed far away (d=50 km) from the base station comparing with the deployment area (ρ=0.1 km) and the energy consumption of data sharing negligibly affects the network's lifetime. Thus, the energy consumed on long distance transmissions dominates compared with the energy consumed on data sharing.

In addition, the authors in (Luskey et al., 2006) also discuss the energy saving of utilizing collaborative beamforming over the transmission of a single sensor node accounting the additional total overhead that comes for its implementation. According to this work, the total network's overhead is related with the number of nodes that participate in procedure and it can be further analyzed in the following terms:

- E_{synch}: the energy consumed in synchronizing,
- E_{pos}: the energy consumed in calculating of each node's precise position,
- E_{distr}: the energy consumed in distributing of the data to all nodes,
- E_{pre}: the energy consumed in communication operations prior to collaborative transmission such as modulation, mixing, filtering and
- E_{digit}: the energy consumed in performing all calculations associated with synchronization and beamforming (except the position estimation).

Consequently, the overall energy balance depends on how the energy saving and energy overhead scale with network size. This implies that the overhead energy is a critical issue due to the demand of positive energy profit that is still open and depends on the considered implementation scheme of collaborative beamforming.

Furthermore, a modern mathematical formulation of the problem under consideration can be presented using game theory in order to control the power consumption of wireless devices (Betz & Poor, 2008). According to this work, cooperating nodes form clusters to retransmit local data to faraway destinations. Multiple clusters are transmitting at the same frequency and at the same time. A non-cooperative game is considered, where the clusters are considered as players and each cluster chooses its average transmit power in order to selfishly optimize its utility function that is expressed as the ratio of the throughput to transmit power. Thus, this work combines the cooperative technique of collaborative beamforming with a non-cooperative game. In general, cooperative approaches can achieve better results, but they usually introduce great cost for centralized control in large networks. The proposed game has a Nash equilibrium, which is unique. Moreover, the utility at the Nash equilibrium has been shown numerically to be significantly higher than if all nodes transmit at maximal average transmit power.

Finally, the authors in (Pun et al., 2009) propose an energy-efficient opportunistic collaborative beamforming scheme for ad hoc sensor networks that suffer from Rayleigh fading. This scheme is a fusion of collaborative beamforming and opportunistic node selection. In contrast to conventional collaborative beamforming schemes where each relay node uses accurate CSI to compensate its channel phase and carrier offset, in the proposed scheme the collaborative nodes are selected by the destination and do not perform any phase compensation. The authors note that the proposed scheme differs from opportunistic beamforming schemes, which consider the data transmission scheduling from a given source to the optimum destination exploiting multi-user diversity.

Considering the opportunistic collaborative beamforming model, the destination node broadcasts a node selection vector to the available nodes in order to opportunistically select a subset of them. Since the selection vector only indicates which relay nodes will participate in the collaborative beamforming and does not convey any CSI, only 1-bit of feedback is required per node. Thus, the total transmitted feedback from the destination is a single K-bit vector. Also, the nodes do not need to adjust their phases prior to or during transmission. The important issue in this scheme is the computation of the selection vector. In particular, this vector is calculated by the destination, aiming at maximizing the power gain of the collaborative beamformer. However, these calculations are exponentially complex in the number of available nodes and the authors propose three low-complexity sub-optimal node selection rules (the sector-based, the iterative greedy, and the iterative pruning) that provide near-optimum beamforming. Theoretical analysis shows that the received signal power at the destination scales linearly with the number of available nodes under a fixed total power constraint, similar with the ideal collaborative beamforming.

4. Conclusion

This chapter studied the state of the art techniques employing energy efficiency in wireless ad hoc and sensor networks. Due to the battery powered nodes of these networks, the efficient use of the limited energy resources is necessary in order to prolong networks' lifetime. In the first section, there was a short description of the basic principles of communications' power consumption in wireless systems and afterwards a survey of two advanced techniques that provides energy efficiency was presented. The first technique was opportunistic scheduling, which exploits the random channel fluctuations of wireless networks that are traditionally viewed as a source of unreliability. Due to these channel variations, there is provided the opportunity to schedule data transmissions by choosing the best time (time diversity) or the best user (multi-user diversity) in terms of channel conditions. Data transmission in good channel conditions can save energy. Moreover, the second technique was collaborative beamforming, which uses a set of collaborative nodes that act as a virtual antenna array and form a beam to cooperatively transmit a common signal. Each node can use lower transmission power and save energy, since the energy consumption is spread over multiple transmitters.

The opportunistic and collaborative techniques, which are mostly designed in Physical and MAC layer, can be seen as the basis of the generalized framework of opportunistic (and collaborative) computing (Conti et al., 2010) that mainly refers in upper layers. This concept considers the opportunistic and collaborative use of any resource available in the network, exploiting the functionality of the other available devices in the environment and maybe changing node roles during runtime (Avvenuti et al., 2007).

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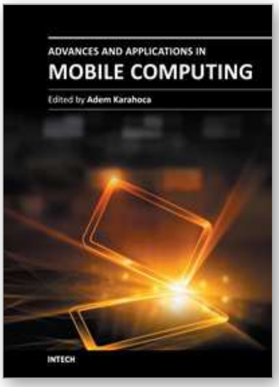

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Advances and Applications in Mobile Computing offers guidelines on how mobile software services can be used in order to simplify the mobile users' life. The main contribution of this book is enhancing mobile software application development stages as analysis, design, development and test. Also, recent mobile network technologies such as algorithms, decreasing energy consumption in mobile network, and fault tolerance in distributed mobile computing are the main concern of the first section. In the mobile software life cycle section, the chapter on human computer interaction discusses mobile device handset design strategies, following the chapters on mobile application testing strategies. The last section, mobile applications as service, covers different mobile solutions and different application sectors.