Mixed TDMA/Simultaneous-Transmission Scheduling for Delay Sensitive Applications

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***Abstract*—Interference represents one of the key limitations in wireless networks. Hence, simple scheduling algorithms, like TDMA, are used in most low complexity wireless networks to mitigate interference. However, TDMA scheduling gives small time slots for different users, and hence, transmitters need to transmit with higher energies to meet the delay deadlines in delay sensitive applications. On the other hand, when multiple users sends their data simultaneously, the links may interfere with each other and higher transmit energies may be needed to meet the delay deadline. In this paper, we start by studying the minimum energy required for different transmit-receive pairs to transmit simultaneously and, at the same time, meet a delay deadline for the individual packets. We show that scheduling the weakly interfering links to transmit simultaneously results in tremendous energy savings, compared to scheduling the links using TDMA. We then propose a mixed TDMA/simultaneous-transmission (TDMA-ST) scheduling scheme that schedules the weakly interfering links to transmit simultaneously and schedule the strongly interfering links to transmit at different time slots. This is especially important for ad-hoc wireless networks, where the nodes locations are not predefined. Simulation results show that, under the same conditions, the proposed mixed scheduling algorithm offers large energy savings, compared to that of pure TDMA scheduling.**

***Index Terms*—Energy efficiency, link scheduling, cross-layer optimization, link adaptation.**

I. INTRODUCTION

Saving transmission energy is one of the key objectives that drives the research in wireless networks with limited energy resources like sensor networks and ad-hoc mobile networks. The scenario considered in this paper is a set of transmitter-receiver pairs that want to transmit their packets in an ad-hoc network. Different transmitters have packets with explicit delay deadlines that need to be received by the receivers before the deadline expires. The orthodox approach to address this scenario is to schedule different links at different time slots using an interference free scheduler (e.g. TDMA or FDMA). TDMA is the choice in many situations because of its simplicity, and due to its ability to mitigate the cross-links interference. Hence, in our previous work in [1] and [2], we have introduced cross layer optimization algorithms based on TDMA schedulers to minimize the total transmitted energy in an ad-hoc network under a delay deadline constraint. However, limiting the scheduling algorithm to TDMA reduces the search space of the optimization algorithms.

In this paper, We introduce a mixed TDMA/simultaneous-transmission scheduling that mixes between TDMA transmission for the strongly interfering links, and the simultaneous transmission of weakly interfering links. We start by studying the feasibility of simultaneous transmission under a delay deadline constraint and introduce an algorithm to find the optimal cross layer parameters that result in minimum energy transmission under delay deadline constraint. We then introduce a mixed TDMA/simultaneous-transmission scheduling and show, through simulations, that it offers big energy savings compared to pure TDMA scheduling.

The energy efficiency formulation presented in this paper is based on cross-layer design as [3], [4], [5], [6], [7]. However, the cross-layer algorithm proposed in this paper targets the total transmission energy minimization over all links and, at the same time, ensures the timely reception of the packets in a multi-user delay-constrained networks. Compared to these previous works, our work has three differences: first, we propose the mixed TDMA/simultaneous-transmission (TDMA-ST) scheduling concept for the purpose of reducing the total transmission energy. In the proposed mixed scheduling, we considered frequency reuse concept, which allows more than one link to be active in the same slot. The proposed frequency reuse concept is quite different than that used in [4], whose goal is to maximize the network's lifetime and different from that used in [7], whose goal is reducing the delay of the optimal flows obtained from the cross-layer optimization model. Second,the proposed framework (i.e., cross layer based energy optimization model and scheduling algorithm) achieves energy minimization objective while satisfying an explicit delay constraint. For example [3] and [4] have focused on lifetime maximization, [7] considered the energy efficiency to achieve a certain packet loss rate while minimizing the delay by incorporating the slot reuse concept, and [8] considered only the end-to-end packet loss rate. Third, the proposed scheduling is flexible and applicable to any network architecture that has multiple users that need to transmit their data within a certain delay constraint.

The remainder of this paper is organized as follows. Section II describes the system model and the optimization problem for the TDMA scheduling. Section III introduces the simultaneous transmission concept. Section IV introduces the

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This work was funded by the Egyptian National Telecommunications Regulatory Authority (NTRA).

978-1-4577-1379-8/12/$26.00 2012 IEEE

mixed TDMA-ST scheduling algorithm. Section V presents the simulation results. Finally, section VII concludes the paper.

II. ENERGY EFFICIENT TDMA SCHEDULING

A. System Model

The system consists of K users that need to send their data, through direct links, to their destinations within a delay deadline D_l. All links operate in the same frequency band. Hence, the spectral resources are allocated to the links in time domain using TDMA scheduling. I_{ij} is the interference from the transmitter of link i to the receiver of link j. A link gain matrix G is defined, where g_{ij} is the gain from the transmitter of link j to the receiver of link j, for $j \neq i$. The diagonal entries g_{ii} represent the gain over each link i. For a path loss model, where the received power decays monotonically with the distance from the transmitter, $g_{ij} = \kappa / d_{ij}^4$, where κ is a constant equal to $\kappa = 10^{-3} m^4$ and d_{ij} is the distance between the receiver of link j and transmitter of link i as in [9]. A simple two link model is illustrated in Figure 1 .

B. Energy-aware cross layer design under TDMA scheduling

In this section, we review the energy-aware cross layer designs in TDMA networks, which were presented in details in our previous work [1] and [2]. All related parameters in the model are defined in the same way as in [2]. In the rest of the paper, it is assumed that all delay deadlines of users' packets are the same and equals to D_l. We consider the problem of computing a minimum-energy joint scheduling and link adaptation strategy to transfer all users' data packets with a delay deadline D_l. Because TDMA scheduling is used, the delay deadline D_l can be satisfied if $\sum_{j=1}^{K} t_j \leq D_l$, where t_j is the transmission time for user j. This constraint ensures that the last transmitted packet will arrive to its destination before D_l. In the scienario studied in this paper, routing is not considered as each user transmits its packet to their destinations through single hop. For a single link i with bandwidth w, the data rate is

$$r_i = w \log_2(1 + k\gamma) \tag{1}$$

where $k = -1.5/\log(5 \cdot \mathrm{BER})$ as in [10] and γ is the signal to noise ratio at the receiver side, defined as

$$\gamma = \frac{P_r}{N_0 \cdot w} \tag{2}$$

where N_0 is the noise spectral density and P_r is the received power. We allow r_i to take all values in $\mathbb{R}_+$. From (1) we get

$$\gamma = \frac{(2^{r_i/w} - 1)}{k} \tag{3}$$

From (2) and (3) we get

$$P_r = \frac{N_0 \cdot w}{k}(2^{r_i/w} - 1) \tag{4}$$

A deterministic path loss model, similar to [10], is used, where

$$P_r = P_t \, \frac{g_t \cdot g_r \cdot \lambda^2}{(4\pi d)^2} = P_t \cdot \alpha \tag{5}$$

where P_t is the transmitted power, g_t is the transmit antenna gain, g_r is the receive antenna gain, λ is the wavelength and α is the overall path loss. We define the link cost x_i as

$$x_i = \frac{k \cdot \alpha}{N_0 \cdot w} \, |h_i|^2 \tag{6}$$

where $|h_i|$ is the fading channel magnitude for link i. Therefore, the required transmission energy over link i to send a packet of length l with rate r_i using TDMA scheduling is

$$e_i^{TDMA} = \frac{l_i}{r_i x_{ii}}(2^{r_i/w} - 1)N_0 \tag{7}$$

The objective of the optimization problem is to minimize the total transmission energy to send all users' packets over all links between all sources-destinations pairs, under a constraint that each packet must be received at its destination before its delay exceeds the delay deadline D_l. Therefore, the problem of minimizing the total transmission energy can be written as

$$\begin{aligned} &\min \left(\sum_{j=1}^{K} \frac{l_j}{r_j x_j}(2^{r_j/w} - 1) \right) \\ &\text{such that} \\ &\sum_{j=1}^{K} \frac{l_j}{r_j} \leq D_l \end{aligned} \tag{8}$$

It is assumed that the links' gains are constant during the packets transmission from the sources to destinations. This optimization problem can be approximated by a convex problem as in [1] and can be efficiently solved using known techniques [11]. By solving the optimization problem in (8), the transmission rates in all links can be calculated.

III. SIMULTANEOUS TRANSMISSION

A. Motivation

The main motivation of introducing the new mixed scheduling algorithm is that in TDMA scheduling, or any other interference-free scheduling algorithm, there is no interference in the network. However, each link gets small period of time to transmit its data. Therefore, the transmission energy will increase to satisfy the delay constraint. Given a fixed number of bits to transmit over a link, transmission energy can be reduced by scheduling transmission for a longer period of time. Hence, weakly interfering links can be scheduled together to give the simultaneously transmitting links longer durations to transmit the same amount of data. On the other hand, links that strongly interfere with each other should be scheduled at different times using an interference-free scheduler, to decrease the average power consumption on these links [5]. In simultaneous transmission, more than one link can send in the same time slot, therefore, they will get a larger amount of time to transmit their data, and the transmission energy will reduce. On the other hand, in simultaneous transmission, interference will increase. Thus, simultaneous transmission can result in lower energy consumption due to activating links for a longer time, or it can result in higher energy consumption due to interference. Choosing the right links to be scheduled together will be discussed in the next section.

B. Feasibility of simultaneous transmissionx

we study the feasibility of simultaneous transmission of packets of different users. If feasible, we find the optimal transmission energies of different transmitters to minimize the overall transmission energies while satisfying the delay deadline. Before going into the general model with K users, we study a simple network with two interfering transmit-receive pairs. The model is shown in Figure 1, where there are two users, each need to send a packet l. The two users need to send their packets within a delay deadline D_l, at the same time and at the same frequency band. For simultaneous transmission, by using the same analysis as Section II-B, the two links will transmit simultaneously with energies

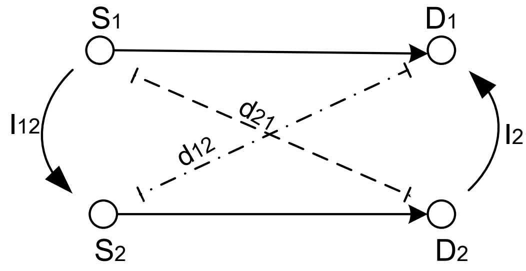

Fig. 1. Two links interference model.

$$e_1^S = \frac{l_1}{r_1 g_{11}}(2^{r_1/w} - 1)(N_0 + I_{21}) \tag{9}$$

$$e_2^S = \frac{l_2}{r_2 g_{22}}(2^{r_2/w} - 1)(N_0 + I_{12}) \tag{10}$$

where

$$I_{12} = e_1^S \cdot g_{12} \tag{11}$$

$$I_{21} = e_2^S \cdot g_{21} \tag{12}$$

Substituting from (11) and (12) in (9) and (10), the transmitted energies of the two sources will then be

$$e_1^S = \frac{\frac{l_1(2^{r_1/w}-1)}{r_1 g_{11}} N_0 + \frac{l_1 l_2 (2^{r_1/w}-1)(2^{r_2/w}-1)}{r_1 r_2 g_{11} g_{22}} g_{21} N_0}{1 - \frac{l_1 l_2 (2^{r_1/w}-1)(2^{r_2/w}-1)}{r_1 r_2 g_{11} g_{22}} g_{21} g_{12}} \tag{13}$$

$$e_2^S = \frac{\frac{l_2(2^{r_2/w}-1)}{r_2 g_{22}} N_0 + \frac{l_1 l_2 (2^{r_1/w}-1)(2^{r_2/w}-1)}{r_1 r_2 g_{11} g_{22}} g_{12} N_0}{1 - \frac{l_1 l_2 (2^{r_1/w}-1)(2^{r_2/w}-1)}{r_1 r_2 g_{11} g_{22}} g_{21} g_{12}} \tag{14}$$

From (13) and (14), and to have a feasible solution, there is a constraint on the cross-links gain (i.e. g_{21} and g_{12}) between links that can be scheduled to send simultaneously

$$\frac{l_1 l_2}{r_1 r_2 g_{11} g_{22}}(2^{r_1/w} - 1)(2^{r_2/w} - 1) g_{21} g_{12} < 1 \tag{15}$$

Therefore, strongly interfering links cannot be scheduled to send simultaneously. Following the same methodology, for three links to transmit simultaneous, they will transmit with energies

$$e_1^S = \frac{l_1}{r_1 g_{11}}(2^{r_1/w} - 1)(N_0 + I_{21} + I_{31}) \tag{16}$$

$$e_2^S = \frac{l_2}{r_2 g_{22}}(2^{r_2/w} - 1)(N_0 + I_{12} + I_{32}) \tag{17}$$

$$e_3^S = \frac{l_3}{r_3 g_{33}}(2^{r_3/w} - 1)(N_0 + I_{13} + I_{23}) \tag{18}$$

where

$$I_{ij} = e_i^S \cdot g_{ij} \tag{19}$$

By substituting from (19) in (16), (17) and (18) we will have

$$e_1 = \frac{l_1.(2^{r_1/w}-1)}{r_1} N_0 + \frac{l_1.(2^{r_1/w}-1)g_{21}}{r_1 g_{11}} e_2 + \frac{l_1.(2^{r_1/w}-1)g_{31}}{r_1 g_{11}} e_3$$
$$e_2 = \frac{l_2.(2^{r_2/w}-1)}{r_2} N_0 + \frac{l_2.(2^{r_2/w}-1)g_{12}}{r_2 g_{22}} e_1 + \frac{l_2.(2^{r_2/w}-1)g_{32}}{r_2 g_{22}} e_3$$
$$e_3 = \frac{l_3.(2^{r_3/w}-1)}{r_3} N_0 + \frac{l_3.(2^{r_3/w}-1)g_{13}}{r_3 g_{33}} e_1 + \frac{l_3.(2^{r_3/w}-1)g_{23}}{r_3 g_{33}} e_2$$

For a general network with N links that need to transmit simultaneously, we will have

$$A \cdot E = Q \tag{20}$$

where

$$E = \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_N \end{bmatrix} \tag{22}$$

, and

$$Q = \begin{bmatrix} \frac{l_1.(2^{r_1/w}-1)g_{11}}{r_1 N_0} \\ \frac{l_2.(2^{r_2/w}-1)g_{22}}{r_2 N_0} \\ \vdots \\ \frac{l_N.(2^{r_N/w}-1)g_{NN}}{r_N N_0} \end{bmatrix}. \tag{23}$$

A is the interference matrix defined in (21). Solving (20) will result in the required transmitted energies from the different sources to meet the delay deadline. If solving (20) resulted in an energies matrix E with any negative element, then the links can not be scheduled for simultaneous transmission. This is equivalent to the condition (15) for the two links scienario.

IV. A MIXED TDMA/SIMULTANEOUS-TRANSMISSION SCHEDULING

In this section, we propose an algorithm that finds the optimum scheduled links which can transmit simultaneously in one time slot in a TDMA system. After defining the scheduled links, this algorithm calculates the transmission rate for each link that minimizes the total transmission energy. In the following analysis, there are N transmitters that need to send their data through N links to their destinations. In the previous two sections, we discussed the TDMA scheduling and the simultaneous transmission. The proposed cross-layer algorithm will use both TDMA scheduling and simultaneous transmission to reach to the optimum transmission energy for each link that satisfies our constraints. The final goal of the algorithm is to find the users that belongs to the set L_{TDMA},

$$A = \begin{bmatrix} 1 & \frac{-l_1.(2^{r_1/w}-1)g_{21}}{r_1 g_{11}} & \frac{-l_1.(2^{r_1/w}-1)g_{31}}{r_1 g_{11}} & \cdots & \frac{-l_1.(2^{r_1/w}-1)g_{N1}}{r_1 g_{11}} \\ \frac{-l_2.(2^{r_2/w}-1)g_{12}}{r_2 g_{22}} & 1 & \frac{-l_2.(2^{r_2/w}-1)g_{32}}{r_2 g_{22}} & \cdots & \frac{-l_2.(2^{r_2/w}-1)g_{N2}}{r_2 g_{22}} \\ \vdots & & \ddots & & \vdots \\ \frac{-l_N.(2^{r_N/w}-1)g_{1N}}{r_N g_{NN}} & \cdots & \frac{-l_N.(2^{r_N/w}-1)g_{N-2N}}{r_N g_{NN}} & \frac{-l_N.(2^{r_N/w}-1)g_{N-1N}}{r_N g_{NN}} & 1 \end{bmatrix} \tag{21}$$

which is the set of links that will use TDMA transmission, and L_s, which is the set of links that will send simultaneously. The main steps of this algorithm are as follows:

1) Start by assuming TDMA scheduling for all N links(all users belong to L_{TDMA}, and L_s is empty) , and find the optimum transmission rates, using (8), for all users.
2) Calculate the total transmission energy for all users $E_{total} = \sum_{i \in L_s} {e_i}^s + \sum_{j \in L_{TDMA}} e_j^{TDMA}$
3) Find the link l_{max} that transmits with maximum energy where $l_{max} = arg\ max_{n \in L_{TDMA}} e_n^{TDMA}$
4) Find the link l_{min} that has minimum interference on the link l_{max}, where
$l_{min} = arg\ min_{n \in L_{TDMA}, n \neq l_{max}} (I_{nl_{max}} + I_{l_{max}n})$
where
$I_{nl_{max}} = e_n^{TDMA} \cdot g_{nl_{max}}$, $I_{l_{max}n} = e_{l_{max}}^{TDMA} \cdot g_{l_{max}n}$
and N_s is the number of the links in L_s.
5) Add l_{max} and l_{min} to L_s.
6) Follow one of the following two proposed schemes to get the rate for each user
1) Optimum rates calculations: Solve the optimization problem

$$\min \left(\sum_{i \in L_s} {e_i}^s + \sum_{j \in L_{TDMA}} e_j^{TDMA} \right) \tag{24}$$

such that

$$l/r_s + \sum_{i \in L_{TDMA}} \frac{l}{r_i} \leq D_l$$

where r_s is the transmission rate of the links that will be active simultaneously. Note that all links in L_s will transmit with the same rate, and their packets will take the same amount of time to reach their destinations. The other links (L_{TDMA}) will use the rest of the TDMA scheduling and user i will transmit with rate r_i. By solving this optimization problem, we get the rates for the users that will transmit simultaneously r_s and the rates for the users that will transmit with no inteference r_i.
2) Suboptimum rates calculations: In this method, we will use the rates that we get from step (1) using TDMA. The users in L_s will send in a longer aggregated time slot. Hence, the new rates for the users in L_s will be $r_s = 1/(\sum_{i \in L_s} 1/r_i)$. The rest of users will use the same rate as step (1).
7) Calculate the new total transmission energy E_{total}^{new} as in step (2).
8) If $E_{total}^{new} \leq E_{total}$, then repeat from step (3) to update L_s with a new link, else remove l_{min} from L_s (Till now, we found the first optimum sharing group of links that will use simultaneous transmission scheduling. Then, we will try to find other sharing groups of links).
9) Repeat from step (3) for the remaining L_{TDMA} links and get, if possible, the optimum second sharing group and so on. Figure 2 illustrates the slot allocation in TDTMA-ST and TDMA for five users need to send their data with in delay deadline D_l.

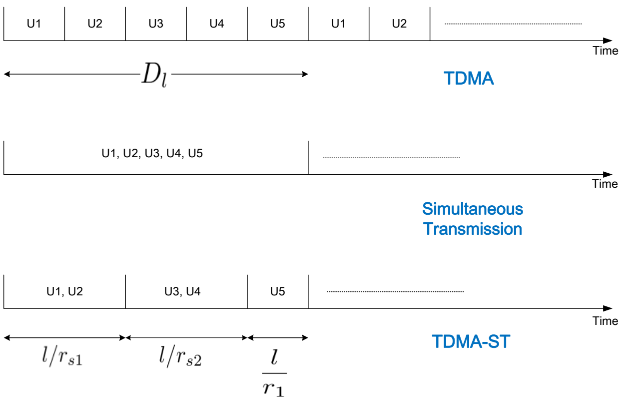

Fig. 2. An example for the slot allocation in TDTMA-ST and TDMA.

V. SIMULATION RESULTS

In this section, the performance of the mixed scheduling algorithm in section (IV) is compared to pure TDMA scheduling. The simulation parameters used are given in Table I. It is assumed that all users' packets have the same length l. To model small scale channel variations, Rayleigh flat fading is used for each link. In the rest of the paper, TDMA-ST stands for mixed TDMA-Simultaneous transmission scheduling.

TABLE I
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
N_0	-174 dBm	λ	0.12 m
l	1000 bit	BER	10^{-4}
Doppler frequancy	0.1 Hz	w	50 kHz

In Figure 3, a simple two-link model as in Figure 1 is considered. This model illustrates the tradeoff between energy savings by interference mitigation, as in TDMA, and the savings by scheduling the weakly interfering links together as in the proposed mixed scheduling algorithm. We compare the total transmission energy in TDMA and the proposed mixed scheduling with varying the delay deadline and the interference, where d_{min} is the minimum distance between the two links that make the constraint in (15) satisfied. We assume that $d_{12} = d_{21} = d_{min} = 10m$. From this figure, at low interference, which corresponds to a longer distance, for all delay deadlines, TDMA-ST has always lower energy consumption compared to TDMA. At high interference, there are two cases: at small delay deadlines, the TDMA-ST has lower transmitted energy than the TDMA, while at large delay deadline, the TDMA-ST has higher energy consumption than the TDMA. We can conclude that, at small delay deadline, the long transmission time for each link is the dominant factor that affects the transmission energy, as in (9) and (10). Therefore, the TDMA-ST which increases the transmission time for each link will have less energy than TDMA. On the other hand, at large delay deadlines, the value of interference between the links, that transmit simultaneously, is the dominant factor that affects the transmission energy. Therefore, TDMA scheduling, which has no interference, will have less energy than TDMA-ST.

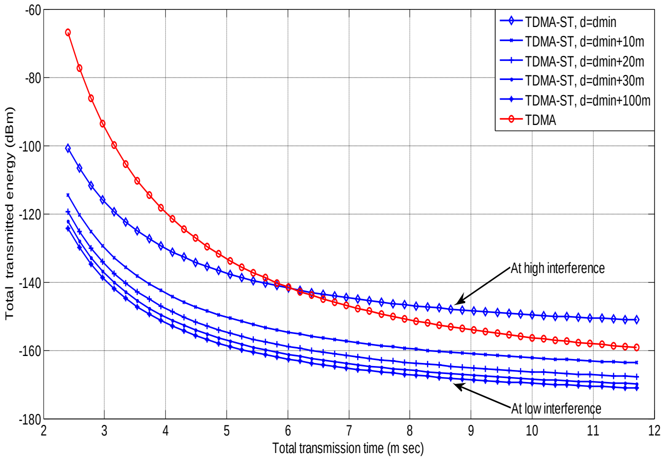

Fig. 3. A comparison between TDMA-ST and TDMA for the two links model.

In Figure 4, we plot the maximum allowed cross-link gain, from the constraint in (15), versus the delay deadline, for the two-link model in Figure 1. As delay deadline increases, we can accept more interference between two links. Therefore, at small delay deadlines, weakly interfering links only can be scheduled together. While at large delay deadline, more links can be scheduled together.

Figure 5 compares between the proposed cross-layer algorithm that uses TDMA-ST scheduling with the cross-layer algorithm that uses TDMA scheduling [2]. It is assumed that there are three users, each user transmits a packet l. Let the gain matrix be given by

$$G = \begin{bmatrix} 0 & -377.8 & -410.24 \\ -377.8 & 0 & -377.8 \\ -410.24 & -377.8 & 0 \end{bmatrix} \text{ dB} \qquad (25)$$

As we can see, as the number of weakly interfering links that transmit simultaneous increases, the total transmitted energy

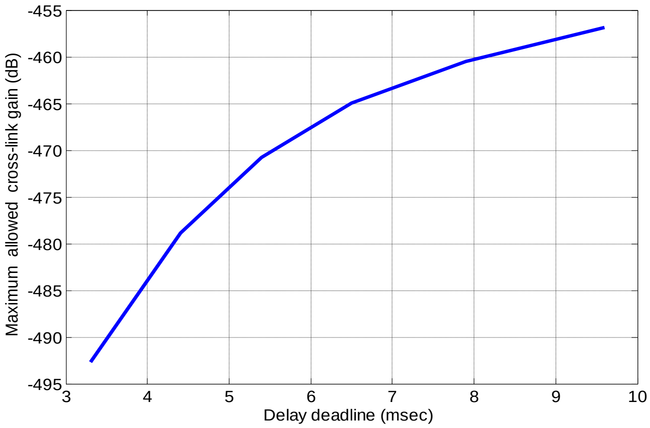

Fig. 4. Maximum allowed cross-link gain versus the total transmission time in case of using TDMA-ST scheduling.

reduces, with condition that all constraints are satisfied (delay constraints and cross-link gain constraints). Figure 5 illustrates also the difference between the two proposed methods (Section IV) that used to calculate the users' rates. At small delay deadlines, the optimum rates calculations method has less energy consumption than the suboptimum rates calculations method, because the optimum rates calculations solve the optimization problem in (24) to find the optimum rates for TDMA-ST scheduling, while the suboptimum rates calculations method used the initial rates of TDMA scheduling to get the new rates in TDMA-ST scheduling. At large delay deadlines, the optimum rates calculations method and the suboptimum rates calculations method have the same transmitted energy, because at large delay deadline the transmitted energy becomes less sensitive to small variation in rates.

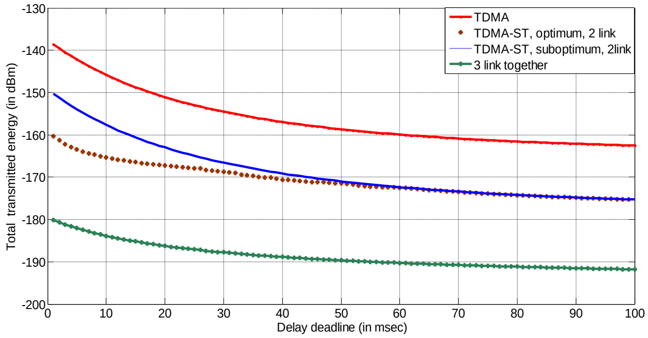

Fig. 5. Comparison of total transmitted energy for different proposed algorithms.

VI. CONCLUSION

In this paper, we proposed a cross-layer algorithm to determine the modulation type, the transmitted energy and the scheduled users in a way to minimize the overall transmission energy while taking into account the given packets delay constraints and BER. To optimally minimize the total transmission energy, a mixed TDMA/simultaneous-transmission scheduling was presented. In the proposed TDMA-ST, few links can send simultaneously, therefore they get a larger amount of time to transmit their data, and the transmission energy will decrease. The proposed cross-layer algorithm uses TDMA-ST scheduling to minimize the transmission energy for all links, while satisfying the delay deadline constraints. Simulation results show that, under the same conditions, the proposed cross-layer algorithm has less energy consumption than the cross-layer algorithms using pure TDMA scheduling.

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