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Energy-Efficient and Reliable Wireless Message Scheduling for Mission-Critical Cyber Physical Systems

Wei Jiang, Jinyu Zhan, Zhengwei Chang, Nan Sang

School of Computer Science and Engineering,
University of Electronic Science and Technology, Chengdu 611731, China,
(e-mail: {weijiang, zhanjy, changzw, sn}@ uestc.edu.cn)

Abstract: A mission-critical application model under asymmetric, unreliable wireless links is established for cyber physical systems. Based on reliability-guaranteed mechanism, deadline-guaranteed mechanism and online slack reclaiming mechanism, a low energy-consumption messages scheduling algorithm under reliability and real-time constraints is proposed and proved to be a low time complexity approach. The proposed algorithm can transmit messages with minimal energy without violating their dependable requirements. Simulations show the superiority and effectiveness of the proposed algorithm on energy-saving and reliability-improving.

Keywords: mission-critical cyber-physical system, energy-efficiency, reliability, message scheduling

1. INTRODUCTION

With the rapid development of Cyber-Physical Systems (CPS) and wireless networks (Sha, 2008 and Wan, 2011), research on **M**ission-**C**ritical **C**yber-**P**hysical **S**ystem (**MCCPS**) in wireless environments has become a hot topic. Examples of wireless MCCPS are military wireless sensor networks, flight control systems, satellite communication systems (Tarello, 2008), body-area networks, and radar tracking systems. On one hand, energy is a key factor for MCCPS. Many wireless devices applied in mission-critical area are battery-powered, and even untethered, so much more energy consumption will result in early failure of devices. On the other hand, dependability factors like real-time and reliability are required for MCCPS (Sha, 2008), because failures of most mission-critical systems may result in great loss of finance, life and even disaster to the earth (Jiang 2010). Therefore, to schedule low-energy, real-time, and reliable messages in MCCPS in wireless environments is imperative and significant work.

Real-time and energy efficiency are basic requirements for transmitting messages in wireless MCCPS. Considering energy and thermal factors, authors of (Tang, 2010) designed a unified methodology to schedule tasks for distributed cyber-physical systems. An energy-minimized service scheduling policy was proposed for time-constrained cyber-physical systems (Jiang, 2008). In (Tarello, 2008), an energy-efficient scheduling policy with individual packet deadline constraints was developed. In (Qin, 2007), an EDF based energy-efficient scheduling algorithm was devised for periodic real-time packets. In (Ruan, 2011), an energy-efficient scheduling mechanism was proposed for aperiodic real-time messages. Ref. (Chen, 2008) dealt with the problem of transmission scheduling of data over a wireless fading channel with a single deadline constraint. Ref. (Zhong, 2008) studied system-level energy optimized message transmitting policy. However, above-mentioned schemes significantly ignore the reliability of messages, thus these work can not be used directly for MCCPS.

Recently, some work has focused on the reliability of CPS (Lee, 2008, and Wu, 2011). A simplex reference model was established to limit fault propagation by unreliable components in CPS architecture (Crenshaw, 2007). Considering the unreliability of wireless link, some references researched on reliability-improving mechanisms. In (Cao, 2006), an energy-efficient communication model was proposed under the asymmetric reliability of wireless links. A hybrid multi-path routing scheme was designed to improve both the security and reliability of applications in hostile and unreliable wireless sensor network (Low, 2009). An adaptive and flexible fault-tolerant communication scheme was designed for body sensor network (Wu, 2010). These studies concentrate on the reliability of data delivery under different network layer, but they did not consider the strict real-time constraints and strict reliability requirements of messages.

As a supplement, this paper makes efforts on dependable message scheduling mechanisms in wireless MCCPS. Incorporating wireless link layer and MAC layer effectively, this paper focuses on how to schedule messages energy-efficiently with guaranteed real-time and reliability.

The rest of this paper is organized as follows. System model and optimization problem are established in Section 2. Three mechanisms are provided to transmit energy-efficient and reliable wireless messages in Section 3 and a heuristic scheduling algorithm is presented in Section 4. Simulation results are discussed in Section 5 and conclusions are drawn in Section 6.

2. SYSTEM MODEL AND OPTIMIZATION PROBLEM

This section introduces the application architecture, establishes the message model under dependable requirements (real-time and reliability) and the energy consumption model of messages, and identifies the system scheduling problem.

2.1 Architecture for Wireless MCCPS Application

In this paper, a MCCPS application system with a critical server and multiple users is considered, like backbone nodes in wireless mesh network, satellite nodes serving multiple users, and sink nodes in wireless sensor networks. The application architecture is demonstrated in figure 1. S is the server node, which is responsible to deliver mission-critical messages to each user, $U=\{U_1,U_2,...,U_m\}$ describes m user nodes, which take charge of receiving messages and feed back to the sever node. Considering the asymmetric reliability of wireless link, $P(S,U_i)$ is the error probability of sending one message to U_i by S, $P(U_i,S)$ is the error probability of sending acknowledgement message to S by U_i, where $P(S,U_i)\neq P(U_i,S)$. The reliability of wireless link can be measured by LQI (Cao, 2006) and CQI mechanism. As the core of our application architecture, the mission-critical message scheduler in S schedule mission-critical messages through real-time, reliable, low-power transmitting and slack reclaiming mechanisms.

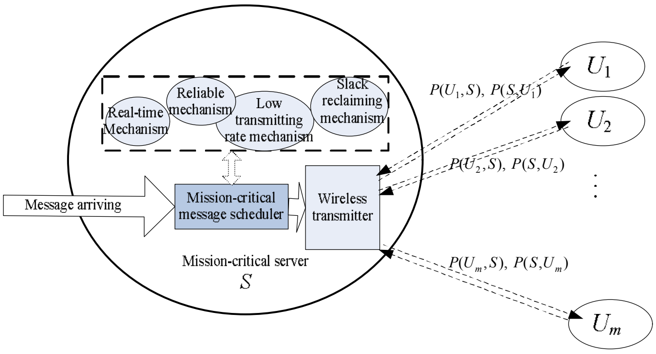

Fig.1. Architecture of wireless MCCPS application

2.2 Model of Mission-critical Messages

This paper focuses on aperiodic messages with strict real-time and reliability constraints. Messages are assumed to arrive arbitrarily and be scheduled by Earliest Deadline First (EDF) policy. Each mission-critical message is modelled by a eight-tuple $M_i=\{A_i,F_i,D_i,L_i,Rate_i,\omega_i,R_i,U_i\}$, which is denoted by its arrival time A_i, end time of message delivering F_i, relative deadline time D_i, message size L_i, message transmitting rate $Rate_i$, message retransmitting times ω_i, reliability of message R_i, and user node id U_i. Reliability constraint of each message is denoted by $R_i^{\min}\le R_i\le R_i^{\max}$, where $R_i^{\min}$ and $R_i^{\max}$ describe the minimal and maximal reliability requirement separately.

2.3 Energy Consumption Model of Messages

It is assumed that wireless channel is low-varied and the transmitting power and transmitting rate are fixed during the transmission of a message. Wireless channel is supposed to be AWGN channel and wireless interference is ignored (Chen, 2008). According to Shannon capacity formula and the path attenuation (Zhong, 2008), the energy consumption of transmitting M_i once is,

$$\xi(M_i)=\frac{L_iBN_0}{Rate\cdot\alpha(d)}[2^{\frac{2\cdot Rate}{B}}-1] \tag{1}$$

where N_0 is the noise power, B is the bandwidth of wireless channel and $\alpha(d)\propto d^{-2}$ is the path-lose factor. Furthermore, the rate range of transmitter is supposed to discrete, and $Rate^{ee}$ denotes the critical transmitting rate, which means lower rate than $Rate^{ee}$ will result in no more energy-savings (Zhong, 2008).

2.4 System Optimization Problem

This paper strives to schedule mission-critical messages submitted to server S with the purpose of minimal total transmission energy, while satisfying the real-time and reliability requirements. X is denoted as all possible schedules of all messages, and X_i denotes all schedule options of M_i. $x_i\in X_i$ means one schedule option of M_i. Therefore, our schedule can be formulated as

$$J(X)=\min_{x_i\in X}\{\sum_{i=1}^{y}\beta_i\cdot\xi(x_i)\} \tag{2}$$

$$\text{S.T.}\quad Rate^{ee}\le Rate_i\le Rate^{\max} \tag{3}$$

$$R_i^{\min}\le R(x_i)\le R_i^{\max} \tag{4}$$

$$F_i(x_i)\le D_i \tag{5}$$

Where, y is the summed number of messages which arrive and require to be transmitted by server S. β_i is the accept factor of messages. When M_i is accepted by S, $\beta_i=1$, else, $\beta_i=0$. (3) describes the range of transmitting rate, (4) and (5) describe the requirements of reliability and real-time constraints respectively.

3. REAL-TIME AND RELIABILITY GUARANTEED MECHANISM FOR MISSION-CRITICAL MESSAGES

In this section, a new retransmission policy and a deadline-guaranteed mechanism are designed to satisfy the reliability and real-time requirements of messages respectively. Furthermore, an online slack reclaim mechanism is proposed to improve the performance of wireless channel resource.

3.1 Reliable Mechanism

It is of critical importance to transmit message with guaranteed reliability under unreliable wireless channel. Conventional methods retransmit messages when they are failed in transmission, such as ARQ and ETX. Both ARQ and ETX may violate strict reliability requirement of each message. Therefore, a new retransmission policy is proposed, which can satisfy the strict reliability of each message.

Property 1: Given a wireless link (S,U_i), the asymmetric failure probabilities is denoted as $P(S,U_i)$ and $P(U_i,S)$ respectively, thus the probability of successfully transmitting a message to user U_i and receiving acknowledgement by server node S is as follows,

$$\begin{aligned}\overleftrightarrow{P}(S,U_i) &= (1-P(S,U_i))\cdot(1-P(U_i,S)) \\ &= 1-P(S,U_i)-P(U_i,S)+P(S,U_i)\cdot P(U_i,S)\end{aligned} \tag{6}$$

Property 2: When node S will transmit message M_i to node U_i, and the minimal reliability requirement of transmitting M_i is R_i, etc. $1-\{1-\overleftrightarrow{P}(S,U_i)\}^{\omega_i+1}\geq R_i$, then the minimal retransmission times ω_i of M_i with guaranteed reliability R_i is,

$$\omega_i = \left\lceil \log_{1-\overleftrightarrow{P}(S,U_i)}^{1-R_i} \right\rceil - 1 \tag{7}$$

3.2 Deadline Guaranteed Mechanism

Due to the randomicity of arriving, online scheduling for aperiodic applications is assumed to perform only after new message arriving. To keep the feasibility, it is necessary to check whether it is viable to admit the new arrival message. New message is schedulable subjecting to following conditions: 1) the sum of starting time and transmitting time of the new message must be less or equal to its deadline; 2) the deadlines of all low-priority messages should not be violated.

Considering the wireless transmitter with variable rates and messages with compulsive reliability requirements, the following definitions and properties are formulated to guarantee the schedulability of messages.

Assumption 1: If the first transmission for each message failed, then set retransmission rate to be maximal for the sake of reducing transmission delay.

Assumption 2: The transmission rate $Rate_i$ with minimal energy consumption is online assigned when message M_i arrived, and $Rate_i$ is unchangeable during transmission.

Definition 1: The **e**arliest **t**ransmission **t**ime (*ett*) of message M_i is the sum of remaining transmitting time of message M_{cur} and transmitting time of all high-priority messages. That is to say,

$$ett(M_i) = r(M_{cur}) + \sum_{M_k\in\Omega, D_k\leq D_i} L_k\left(\frac{1}{Rate_k}+\frac{\omega_k}{Rate^{\max}}\right) \tag{8}$$

Where, $r(M_{cur})$ is remaining transmitting time of M_{cur} , $\sum_{M_k\in\Omega, D_k\leq D_i} L_k\left(\frac{1}{Rate_k}+\frac{\omega_k}{Rate^{\max}}\right)$ denotes transmitting time of all high-priority messages, Ω denotes ready messages which have accepted but not transmitted.

Property 3: New arrival message M_i is schedulable if following conditions are satisfied,

$$\frac{ett(M_i)+(\omega_i+1)L_i/Rate^{\max}}{D_i}\leq 1 \tag{9}$$

$$for\ \forall M_k\in\Omega, D_k>D_i,\quad \frac{ett(M_k)+(\omega_i+1)L_i/Rate^{\max}}{D_k}\leq 1 \tag{10}$$

From property 3, it can be inferred that if real-time and reliability requirements are satisfied for new arrival message and deadlines of other low-priority messages are not violated, then new message is schedulable. The reason is that new message will not affect the schedulability of high-priority messages in EDF policy.

Property 4: When new arrival M_i needs to be transmitted by $Rate_i$, the following conditions must be satisfied.

$$\frac{ett(M_i)+L_i/Rate_i+\omega_i L_i/Rate^{\max}}{D_i}\leq 1$$

(11)

$$for\ \forall M_k\in\Omega, D_k>D_i,\quad \frac{ett(M_k)+L_i/Rate_i+\omega_i L_i/Rate^{\max}}{D_k}\leq 1 \quad (12$$

3.3 Online Slack Reclaiming Mechanism

Due to the high probability of successfully transmitting a message, there is no need to transmit each message with ω times, thus it will result in some schedule slack. It will be a good approach to improve the effectiveness of wireless channel resource through utilizing these slack times, so an Online Slack Reclaim (OSR) mechanism is designed. OSR can reclaim the idle time, which is allocated to each message but not used. Making use of these slack times, server node can accept more new arrival messages or reduce the transmitting rate of each message, which will improve the throughput and energy efficiency. Without loss of generality, M_{cur} denotes as the currently transmitting message, and transmits successfully at g-th $(g\leq\omega)$ times, then the earliest transmitting time of each message with low-priority in ready queue is formulated as,

$$for\forall M_k\in\Omega, D_k>D_{cur},\ ett^{\#}(M_k)=ett(M_k)-(\omega_k-g+1)\frac{L_{\mathrm{cur}}}{Rate^{\max}} \tag{13}$$

4. ENERGY-EFFICIENT MESSAGE SCHEDULING ALGORITHM

Incorporating aforementioned three mechanisms, this paper devised a **D**eadline and **R**eliability Constrained **E**nergy-

Efficient **P**acket Scheduling (**DREEP for short**). DREEP strives to online minimize the energy consumption of new arrival message by selecting minimal transmitting rate, while not violating real-time and reliability requirements of each message.

```
1: While CMD do
2: Case CMD="New packet $M_i$ arriving":
3:     ScheduleDecision ($M_i$);
4:     Break;
5: Case CMD="Successful transmission of current packet
           $M_{\mathrm{cur}}$ at $g$-th time":
6:     OnlineSlackReclaim( $\Omega$ , $M_{\mathrm{cur}}, g$);
7:     Break;
8: End While

9: Function ScheduleDecision ($M_i$)
10:  $\omega_i = \left\lceil \log_{1-\overleftrightarrow{P}(S,U_{Rv_i})}^{1-R_i} \right\rceil - 1$ ;
11:  $ett(M_i) = r(M_{cur}) + \sum_{M_k \in \Omega, D_k \le D_i} L_k\left(\frac{1}{Rate_k} + \frac{\omega_k}{Rate^{\max}}\right)$ ;
12:  If { $\frac{ett(M_i) + (\omega_i + 1)L_i / Rate^{\max}}{D_i} \le 1$ ;
13:      && For $\forall M_k \in \Omega, D_k > D_i$
14:          $\frac{ett(M_k) + (\omega_i + 1)L_i / Rate^{\max}}{D_k} \le 1$ ;
15:     }
16:    Then
17:      $\Omega = \Omega \cup \{M_i\}$ ; $\beta_i = 1$ ;
18:  End If
19:  $Rate_i = Rate^{\max}$ ;
20:  While $Rate_i > Rate^{ee}$ do
21:    $Rate_i = Rate_i - \Delta Rate$ ;
22:    If { $\frac{ett(M_i) + L_i / Rate_i + \omega_i L_i / Rate^{\max}}{D_i} > 1$
23:      or $\exists M_k \in \Omega, D_k > D_i$
24:        $\frac{ett(M_k) + L_i / Rate_i + \omega_i L_i / Rate^{\max}}{D_k} > 1$
25:      }
26:    Then $Rate_i = Rate_i + \Delta Rate$ ; Break;
27:    End If
28:  End While
29:  Return $x_i = (\beta_i, Rate_i, \omega_i)$ ;
30: End Function

31: Function OnlineSlackReclaim( $\Omega$ ,$M_{\mathrm{cur}}, g$))
32:  $\Omega = \Omega - \{M_{cur}\}$
33:  For $\forall M_k \in \Omega$ , $D_k > D_{cur}$ do
34:    $ett^{\#}(M_k) = ett(M_k) - (\omega_k - g + 1)\frac{L_{\mathrm{cur}}}{Rate^{\max}}$ ;
35:    $ett(M_k) = ett^{\#}(M_k)$
36: End Function
```

Fig.2. Pseudo-code of DREEP algorithm

The procedure of DREEP is described in figure 2. DREEP tests the system events iteratively (line 1-8). When new message arrives, it advocates **ScheduleDecision** function; when a message transmits successfully before ω times, it advocates **OnlineSlackReclaim** function.

In **ScheduleDecision** procedure (line 9-30), DREEP firstly accumulates the retransmission times according the reliability requirement (line 10) and the earliest transmitting time of new arrival message (line 11). Secondly, DREEP tests the schedulability based on property 3 (line 12-18). If the deadlines of new message and other low-priority messages in ready queue are not violated when transmitting new message under $Rate^{\max}$ (line 12-14), then this new message is accepted (line 16-17). After the acceptance of new message, DREEP iteratively tries to reduce the transmitting rate, and choose a real-time guaranteed minimal rate finally (line 19-28). In line 29 the schedule policy x_i of this message is returned. In **ScheduleDecision** procedure (line 31-36), the current message is deleted in read queue when it transmits successfully in advance (line 32), and the earliest transmitting times of low-priority messages in ready queue are updated (line 33-35).

Theorem 1. DREEP is an online scheduling algorithm with low complexity.

Proof. Without loss of generality, it is supposed that there are N messages in ready queue and Q levels of optional transmitting rates. According to the description of DREEP, the complexities of computing retransmission time and earliest transmitting time (line 10 and 11), and testing schedulability of new message (line 12) are all O(1); the complexity of judging the deadline guarantee of low-priority messages in worst case (lines 13-14) is O(N). Obtaining the minimal transmitting rate of new message (lines 20-28) will take O(NQ) in worst case. In OSR stage, updating the earliest transmitting time of ready messages (lines 33-35) will take O(N) time. Thus, complexity of DREEP can be deduced as

$$\mathrm{O(DREEP)} = \mathrm{O}(1) + \mathrm{O}(N) + \mathrm{O}(NQ) + \mathrm{O}(N) = \mathrm{O}(NQ) \tag{14}$$

In practical applications, N and Q are not too great, thus the overhead of DREEP can be ignored comparing to the transmission time. Therefore, DREEP is an online scheduling algorithm with low complexity.

5. EXPERIMENTAL RESULTS

To test the effectiveness of proposed algorithm, a mission-critical wireless node is simulated by VC++. For the sake of comparison, this paper introduced PARM which is an energy-aware real-time message scheduling algorithms (Ruan, 2011), and conducted two variants of DREEP, which are DREEP-ETX and DREEP-NO-OSR. Different with REEP, DREEP-ETX explored the ETX mechanism, while DREEP-NO-OSR ignored the OSR mechanism. Beyond total transmission energy, AR is introduced for performance comparing, which denotes the average reliability of all accepted messages. Based on (Zhong, 2008, and Ruan, 2011), detailed simulating parameters are listed in Table 1.

The first simulation is conducted to evaluate the algorithm performance under different message arrival rates. The number of messages, deadlines, message sizes, reliability requirements, communication distances and link reliability are random generated according to Table 1. Messages are set to arrive with Poisson distribution arrival rate, which ranges from 0.5 No./Sec to 3 No./Sec. Fig. 3 and Fig. 4 demonstrate the simulation results of total transmission energy and average reliability respectively, in which the total transmission energy is normalized. From figure 3, we obtain that the total transmission energy of all algorithms are increased with the raising of arrival rate. This is because quicker arrival rate results in more messages in ready queue, then scheduling slack used to reduce transmitting rate becomes small, which leads to more energy consumption. The energy of DREEP is between PARM and DREEP-NO-OSR, and closes to DREEP-ETX. Specifically, DREEP saves 25.8% energy based on DREEP-NO-OSR, and consumes 37.6% and 4.7% more energy than PARM and DREEP-ETX respectively. For reliability metric in figure 4, the ARs of DREEP and DREEP-NO-OSR are both approximate to 1, which are 99.28% and 99.25% averagely. Without considering reliability factors, AR of PARM is very low with 81.3% averagely, which suggests that PARM is not suitable for reliability-constrained applications. Additionally, the reliability of DREEP is superior to DREEP-ETX with 6.7% improvement. Therefore, it can be obtained that DREEP is an efficient and effective trade-off algorithm, which can reduce much more total transmission energy while maintaining high reliability of messages under different arrival rates.

Table 1. Simulating parameters

Parameters	Values
Wireless channel	AWGN
Channel bandwidth	10^6 Hz
Noise power	1
Wireless rate	250 Kbps ~ 2 Mbps
Number of messages	10000
Arrival rates	0.5~3 No./Sec.
Message sizes	100~800 KB
Deadline of Messages	1000~10000 ms
Reliability requirements	0.98~0.9999
Error probability of link	0.05~0.25
Distance of transmitting	50~200 m

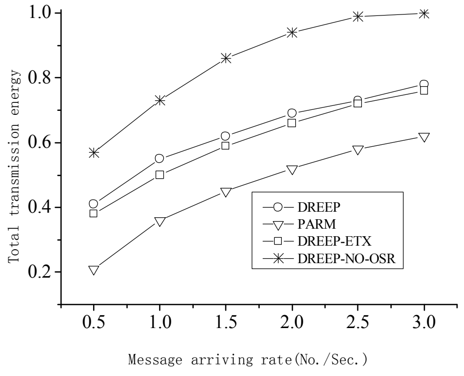

Fig.3. Impacts of arrival rate on total energy consumption

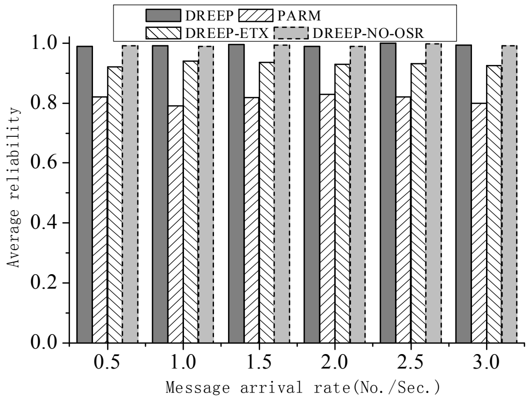

Fig.4. Impacts of arrival rate on message reliability

The goal of the second simulation is to test the impacts of message deadlines. Arrival rate is fixed as 1No./Sec, and the average deadline of messages varies from 2000ms to 7000ms. All other simulated parameters are the same as first simulation. From figure 5, total transmission energy of all algorithms is decreasing with the increase of deadline. The reason is that longer deadline leads to higher probability of reducing transmission rate, which results in reducing of total transmission energy. From figure 6, some conclusions can be drawn: 1) the total transmission energy and reliability of PARM are both minimal among all algorithms, which means PARM can not be used to schedule mission-critical messages.; 2) although the energy of DREEP is near the results of DREEP-ETX, the reliability of DREEP is averagely improved by 5.5%. Therefore, DREEP is absolutely superior to DREEP-ETX; 3) The reliability of DREEP and DREEP-NO-OSR are very close, but the energy of DREEP is obviously reduced than DREEP-NO-OSR, which demonstrates the efficiency of OSR mechanism. The second simulation shows the superiority of DREEP on transmission energy saving and reliability improving.

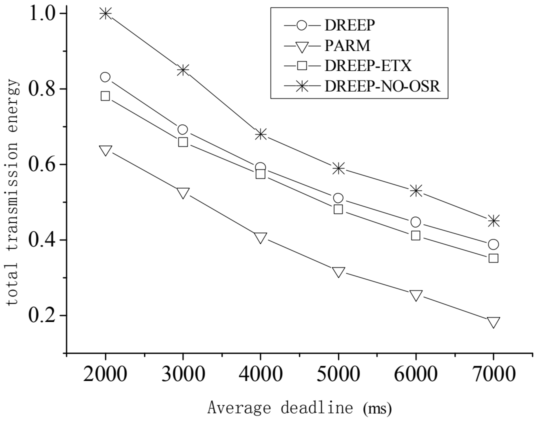

Fig.5. Impacts of deadlines on energy consumption

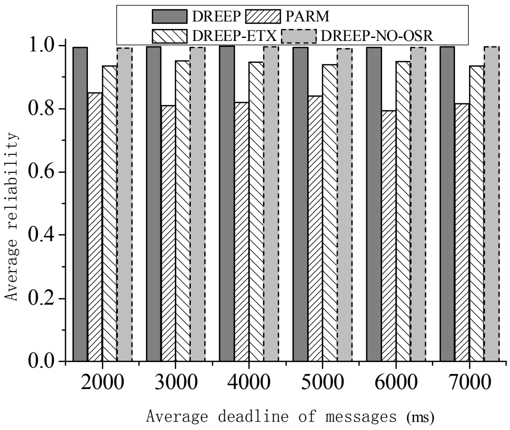

Fig.6. Impacts of deadlines on message reliability

6. CONCLUSIONS AND FUTURE WORK

This paper contributes with a message scheduling algorithm for mission-critical cyber-physical systems under unreliable wireless communication model. The advantages of our proposed algorithm are in satisfying reliability and real-time requirements of individual message by reliability-driven retransmitting mechanism and deadline guaranteed mechanism. Considering the successful transmission in advance, a scheduling slack reclaiming mechanism is further devised to improve system performance. The proposed akgorithm, named DREEP, is proved to be low-time complexity, which is very suitable for online message scheduling. Simulations verified the advantages and effectiveness of DREEP on real-time, reliability and energy-savings.

Incorporating other dependability requirements such as security and extending this study to large scale wireless networks are further researches.

7. ACKNOWLEDGMENT

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