On the Throughput of Wireless Sensor Networks Using Multi-packet Reception

Ming-Fei Guo†, Xinbing Wang‡, Min-You Wu†
†Department of Computer Science and Engineering, Shanghai Jiao Tong University, China
‡Department of Electronic Engineering, Shanghai Jiao Tong University, China
Email: †{mfguo, mwu}@sjtu.edu.cn, ‡xwang8@sjtu.edu.cn

***Abstract*—In wireless sensor networks, the nodes near the sink suffer from heavy traffic load. The recent progresses in physical layer make multi-packet reception (MPR) feasible, which may alleviate the suffering nodes. In this paper, we utilize MPR to improve the throughput of wireless sensor networks while maintain the fairness requirement for each sensor. Firstly, we formulate an optimization problem for wireless sensor networks using MPR. The result of the optimization is an upper bound for the network throughput. Secondly, we give a feasible heuristic scheme. In the performance evaluation, we analyse the throughput gap between the upper bound and the performance of the heuristic scheme. We also study the performance of the heuristic scheme by adjusting several network parameters and the results show that MPR brings notable throughput gain in wireless sensor networks and give some network design implications.**

I. Introduction

As an emerging technology, Wireless Sensor Networks (WSNs) have a wide range of potential applications, including environmental monitoring, military applications, medical care and smart buildings. In a wireless sensor network, the sink receives data from sensors in the network via wireless relay links. Since the nodes near the sink carry much more traffic than the others, the interference among these nodes is heavy and these nodes become the bottlenecks of the network. On the other hand, the radio bandwidth in WSNs is very limited, 19.2Kbps in MICA2 and 250 Kbps in MICAz and Telos. When such a wireless sensor network is deployed in an very active sensing area, the heavy traffic may overwhelm the network.

Recent progresses [1], [2], [3] in physical layer made multi-packet reception (MPR) feasible. Techniques such as multi-user detection (MUD) [1], successive interference cancellation (SIC) [2] and multiple input multiple output (MIMO) [3] have become practical. Thanks to these techniques, a receiver is able to decode several concurrent transmissions. Recently Garcia-Luna-Aceves et al. demonstrated that MPR increase the order of the capacity of 3-D random wireless ad hoc networks by a factor of $\Theta(\log n)$ under the protocol model, which assume that all the transmissions within the receiving range of a node can be decoded, where n is the number of nodes in the network. They also showed that MPR provides a higher capacity gain for ad hoc networks than network coding for a single-source multicast and multi-pair unicasts.

¿From the above analysis, it is clear that using MPR is an attractive approach for alleviating the traffic burden of the sensors near the sink and improve the network throughput. However, there is much work to be done before MPR-based WSNs can be made practical. The transmissions that are to be decoded at a receiver need to be sent synchronously, and the number of concurrent transmissions allowed around a receiver cannot exceed the number of concurrent transmissions that the receiver can decode, which may be smaller than the number of neighbors of the receiver if the network is well connected. Furthermore, the protocols used in traditional ad hoc networks have been designed to avoid mutliple access interference (MAI), however MPR-based WSNs can reduce the negative effects of MAI. For example, the backoff mechanism of IEEE 802.11 DCF select a node to send when more than one transmission occurs around a receiver, although more than one receptions can be concurrent due to MPR.

In this paper, we formulate an optimization problem for MPR-based WSNs and give a feasible heuristic scheme to approximate the result of the optimization problem. We assume that an wireless interface can decode at most k concurrent transmissions within its receiving range and each sensor is equipped with one such wireless interface. Each sensor has a traffic demand designated to the sink and each sensor may forward the traffic of the other sensors. Under such assumptions, we formulate the throughput maximization problem as an optimization problem. Note that in this optimization problem we should maintain the fairness requirement. Otherwise, to maximize the total network throughput, the sensors far away from the sink may starve due to the higher cost of delivering their traffic to the sink. We firstly give the necessary and sufficient conditions for feasible interference free link scheduling, which can be used for the design rules of the heuristic. Secondly, we relax the necessary and sufficient conditions into a linear form for the optimization problem, which are only necessary conditions for feasible interference free link scheduling. The result of the optimization is an upper bound for the throughput of WSNs. The heuristic scheme consists two parts, routing and scheduling. We use the output of the optimization as the routing strategy for the heuristic. Based on this routing scheme, we use a heuristic scheduling scheme to avoid the interference among links. We use the result of the heuristic scheduling as a constraint to re-maximize the network throughput and give a feasible throughput. To address the fairness requirement, we require that the achieved traffic demand ratio of each flow is the same although the traffic demands of the flows may be different.

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The remainder of the paper is organized as follows. Section II summarizes prior related work and presents the contributions of our work. We present the network model in Section III. The problem formulation is in Section IV. Section V gives the feasible heuristic algorithm. The performance evaluation is in Section VI. We conclude our paper in Section VII.

II. Related Work

The problem we study in this paper is essentially a joint routing and scheduling problem. There are considerable works on this topic. We classify these works into two categories based on the research methods.

The first category is asymptotic throughput analysis [4], [5], [6], [7], [8]. These works conclude the relationship between the throughput and the network parameters, i.e., number of nodes, number of radios, in the form of asymptotic function.

The second category is non-asymptotic throughput analysis [9], [10], [11], [12], [13]. These works study the throughput from a more practical perspective, i.e., by formulating an optimization problem, presenting heuristic algorithm and approximate algorithms for the joint routing and scheduling problem. This paper belongs to this category. The other related work includes [14], [15], [16].

From the above survey, we can conclude that the joint routing and scheduling problem has not been solved for wireless sensor networks using MPR.

Our contributions are as follows:

1. We formulate an optimization problem for MPR-based WSNs. We both give sufficient and necessary conditions and necessary conditions for interference free link scheduling. Based on these necessary conditions, we use the optimization tools to give the throughput upper bound. To the best knowledge of us, it is the first work to study the throughput of MPR-based WSNs.
2. Different from [13], we use a more general interference model and our heuristic selects multi-path according to the result of optimization rather than selects several predefined number of paths. Additionally our time fraction assignment to the scheduled link sets is optimal.
3. In our experiments, we evaluate our algorithm in several important practical metrics, such as the achieved traffic demand ratio, the acceptance ratio of network traffic demands. Throughout extensive experiments, we get some valuable implications for the design of MPR-based WSNs.

III. Network Model

A. Notations

We represent a wireless sensor network as a directed graph $G = (V, E)$, where V is the set of nodes and E is the set of links. Each node $u \in V$ has one MPR wireless interface. A special node $c \in V$ represents the sink. We denote the receiving range as R_r, the interference range as R_i and the distance between two nodes u, v as $d(u, v)$. A link $e = (u, v) \in E$ if and only if $d(u, v) \le R_r$ where u is the transmitter of e and v is the receiver of e, we denote them as $t(e)$ and $r(e)$ respectively. Each node $u \in V$ has $I(u)$ interfering nodes. A node $v \in V$ is in $I(u)$, if and only if $R_r < d(v, u) < R_i$. Although the prior work [13] assume that $R_i = R_r$, we use a more general model which assume that $R_i = q \times R_r$ where $q \ge 1$. In our performance evaluation section, we will study how the ratio q impacts the throughput.

B. Assumptions

We assume that each transmission is slotted into synchronized slots of the same length and multi-path routing is used. Different from the model in [4], we assume that a wireless interface can decode at most k concurrent transmissions within its receiving range provided that no interfering node is transmitting at the same time.

IV. Problem Formulation

We formulate the joint routing and scheduling problem in MPR-based WSNs as a multi-commodity flow problem. We do not formulate it as a maximum flow problem as in [11] because in reality a relay sensor should not consume the traffic originated by other sensors (Note that the only data consumer in the network is the sink c) and each flow should has its own flow conservation constraint. Suppose that the traffic demand of a flow m is $l(m)$. Our objective is to maximize the throughput of the sensor network while maintain the fairness requirement. Hence we are searching to find a solution that can maximize a ratio $\psi, 0 \le \psi \le 1$ and the achieved traffic demand for a flow m is $\psi l(m)$. When $\psi = 1$, the traffic demands of the network are accepted otherwise rejected. $x^m(e)$ denotes the amount of the m_{th} flow carried by link e which is measured by kbps. $s(m)$ denotes the source node of m_{th} flow. $t(e)$ denotes the transmitting node of link e. $r(e)$ denotes the receiving node of link e. Hence we have

$$max \psi \tag{1}$$

subject to

$$\sum_{e \in \{e | t(e) = s(m)\}} x^m(e) = \psi l(m), \forall m \tag{2}$$

$$\sum_{e \in \{e | r(e) = c\}} x^m(e) = \psi l(m), \forall m \tag{3}$$

$$0 \le \psi \le 1 \tag{4}$$

To formulate this problem, we firstly give the necessary and sufficient conditions for interference free link scheduling, which will be used as the design rules for the heuristic scheme. In order to build up the optimization formulation, we need to convert these rules into linear form and use them as the necessary conditions for interference free link scheduling.

A. Necessary and sufficient conditions interference free link scheduling

The objective of link scheduling is to ensure that in each time slot the links scheduled for transmission do not interfere with each other according to the network model.

Before introducing the necessary and sufficient conditions, we firstly introduce some notations and definitions. We let $X_{e,\tau}, e \in E$ be the indicator variable where $X_{e,\tau}$ is 1 if and only if link e is active in slot τ. For each link e, we define three kinds of links for it. We denote the first category as $I_1(e)$. A link $e' \in E$ is in $I_1(e)$ if and only if $R_r < d(t(e'), r(e)) \leq R_i$. Any link in $I_1(e)$ will interfere with e, so these links should not be scheduled when e is active. We denote the second category as $I_2(e)$. A link $e' \in E$ is in $I_2(e)$ if and only if $d(t(e'), r(e)) \leq R_r$. A link in $I_2(e)$ can be co-active with e, however such links consume the MPR ability of $r(e)$, hence the number of co-active links should be limited. We denote the third category as $I_3(e)$. A link $e' \in E$ is in $I_3(e)$ if and only if $t(e') = t(e)$ or $t(e') = r(e)$ or $r(e') = t(e)$. The links in $I_3(e)$ cannot be scheduled when e is active, since such links share transmitter or receiver with e and the wireless interface is simplex.

Hence according to our network model, we can present the necessary and sufficient conditions as follows (We ommit the proof for this theorem, since we can easily derive it from the above notations and definitions).

Theorem 1: In any time slot τ, a link schedule S is interference free if and only if S satisfy:

For each link e, when e is active in τ,

$$\sum_{e' \in I_1(e)} X_{e',\tau} = 0 \tag{5}$$

$$\sum_{e' \in I_2(e)} X_{e',\tau} \leq k - 1 \tag{6}$$

$$\sum_{e' \in I_3(e)} X_{e',\tau} = 0 \tag{7}$$

B. Necessary conditions for interference free link scheduling

We have presented the necessary and sufficient conditions for interference free link scheduling and these conditions can be used as the design rules for feasible algorithms, however these conditions are non-linear and hard to be used in our optimization framework. Consequently, we need some linear form conditions to grantee interference free link scheduling to some extent.

Before presenting the necessary conditions, we firstly introduce some notations and definitions. We denote $c(e)$ as the link capacity of link e which is also measured in kbps. We denote $E^+(u)$ as the set of links which has u as the receiver. Similarly $E^-(u)$ is the set of links which has u as the transmitter. Hence we can present the necessary condtions for interference free link scheduling as follows. Due to the limited space, we put the proof in [18].

Theorem 2: If there is an interference free link scheduling, for each node $u \in V$, we must have:

$$\sum_{e \in E^-(u)} \frac{\sum_m x^m(e)}{c(e)} + \frac{1}{k} \sum_{e' \in E^+(u)} \frac{\sum_m x^m(e')}{c(e')} \leq 1, \forall u \in V \tag{8}$$

$$\sum_m x^m(e) \leq c(e)\ , \forall e \in E \tag{9}$$

$$x^m(e) \geq 0, \forall e \in E, \forall m \tag{10}$$

C. Flow conservation constraints

Besides the interference free link scheduling constraints, the optimization problem should also subject to the following constraints:

Flow conservation constraints: We denote $s(m)$ as the source node of the m_{th} flow and denote $l(m)$ as the traffic demand of the m_{th} flow.

$$\sum_{e \in \{e|t(e)=s(m)\}} x^m(e) = \psi l(m), \forall m$$

$$\sum_{e \in \{e|r(e)=c\}} x^m(e) = \psi l(m), \forall m$$

$$\sum_{e \in E^+(u)} x^m(e) = \sum_{e \in E^-(u)} x^m(e), \forall u \notin \{s(m), c\}, \forall m \tag{11}$$

D. Routing Algorithm

After getting all the constraints, we now formulate a linear program (LP1) to find link flows that maximizes ψ subject to these constraints. The resulting LP is given below:

$$max \psi$$

Subject to (2), (3), (4), (8), (9), (10), (12).

Note that this routing algorithm does not consider the interference among the nodes, hence the resulting link flow cannot be achieved practically and the result of the optimization is an upper bound for the network throughput. The result of LP1 will be used for the routing strategy of the heuristic scheme.

V. Heuristic joint routing and scheduling scheme

In this section, we present a heuristic scheme which is feasible in practice. This scheme consists two parts, routing and scheduling respectively. We use the result of LP1 as the route selection. The link scheduling has two phases. In the first phase, we use a heuristic link scheduling algorithm to get a interference free link schedule subject to the necessary and sufficient conditions that we derived in Section IV. The resulting schedule consists of the link sets, each of which consists co-schedulable links. In the second phase, we formulate a linear program for calculating the optimal time fractions assigned to each link set to achieve the maximum ψ.

Algorithm 1 Heuristic link scheduling algorithm

INPUT: $G_{LP_1}(V, E_1)$
OUTPUT: Schedule S
$S = \{\}$
$T = 0$
while $E_1 \neq \{\}$ **do**
  $T = T + 1$
  $S_T = \{\}$
  while Can $= \{e \in E_1 | \{e\} \cup S_T$ is a schedulable set$\}$ $\neq \{\}$ **do**
    $e = \arg \max_{e' \in Can} \sum_m x^m(e')$
    $S_T = S_T \cup \{e\}$
    $E_1 = E_1 - \{e\}$
  end while
  $S = S \cup S_T$
end while

A. Heuristic link scheduling scheme

In this algorithm, the schedule consists several link sets, S_T, where T denotes the length of the schedule. G_{LP_1} denotes the graph reduced from $G(V, E)$ after LP1. The node set in $G_{LP_1}(V, E_1)$ is the same as $G(V, E)$. A link $e \in E$ is in E_1 only if the assigned flow for e is positive, namely $E_1 = \{e \in E | \sum_m x^m(e) > 0\}$. Can is a candidate link set for scheduling.

B. Optimal time fraction assignment

We denote $\delta_T, 0 \leq \delta_T \leq 1$ as the time fraction assigned to link set S_T. Obviously we have:

$$\sum_{S_T \in S} \delta_T = 1 \qquad (12)$$

And the link capacity constraint should be rewritten below:

$$\sum_m x^m(e) \leq \delta_T c(e) \ (e \in S_T), \ \forall e \in E_1 \qquad (13)$$

Hence we can formulate another linear programming problem (LP2) to optimally assign time fractions to the scheduled link sets and find maximum achieved ratio as follows:

$$max\psi$$

Subject to (2), (3), (4), (10), (11), (12), (13)

VI. Performance evaluation

In this section, we evaluate the issued heuristic scheme and compare its performance with the throughput upper bound. The experimental platform is ubuntu 8.0.4. We developed a software in C language with the assistance of lpsolve shared library [17]. Although several topologies were considered, we report here the results for one representative topology. The nodes deployment of the topology is shown in [18]. We consider a connected random network with 1 sink and 49 sensors deployed over a 200×200 square meters area. Each sensor has a traffic demand designated to the sink and the traffic demands were randomly generated in a predefined region.

As shown in Fig. 1, we compare the upper bound and the performance of heuristic scheme for 4 scenarios: ($R_r = 70m, q = 1.5$), ($R_r = 70m, q = 2.0$), ($R_r = 90m, q = 1.5$), ($R_r = 90m, q = 2.0$). We select the receiving range as 70m and 90m, since according to the data sheet of MICAz [19], the outdoor range is 75m-100m. The traffic demand of each sensor is uniformly and randomly generated from 10 kbps to 20 kbps and node 47 is selected as the sink. As shown in Fig. 1, as k increases, the achieved traffic demand ratio increases, however, when k exceed a threshold, there is no notable increase of the achieved traffic demand ratio. Note that the achieved ratio when $R_r = 90m$ is larger than the ratio when $R_r = 70m$. We also note that when interferences become heavier (i.e., q is larger), the throughput degrades. There is a clear gap between the upper bound and the heuristic scheme, the reason is that the upper bound does not consider the interferences (the links in $I_1(e)$ described in Section IV) and is too optimistic.

In Fig. 2, we study how the MPR ability impacts the ratio for the acceptance of network traffic demands. The traffic demand is uniformly and randomly generated from 6 kbps to 12 kbps and node 47 is the sink. As shown in the figure, when k is small, i.e., $k = 1$, the ratio for both scenarios is zero. As we increase k, the acceptance ratio increases dramatically. Comparing the two cases when $R_r = 70m$ and when $R_r = 90m$, we see that the larger the range, the higher the acceptance ratio.

As shown in Fig. 3, we exploit the impact of the sink selection. We select 3 representative nodes as the sink respectively. Node 19 is in the approximate center of the deployment area. Node 13 is in the margin area and node 38 is located between the center and the margin. Fig.3 shows that the achieved traffic demand ratio when sink is node 19 is the maximum and when sink is in 13, the achieved traffic demand ratio is the minimum.

Finally we compare the achieved traffic demand ratio for different average node degree. Fig. 4 shows that as the average node degree increases, the achieved ratio increases.

VII. Conclusion

In this paper, we utilized MPR to improve the throughput of wireless sensor networks. We formulated the joint routing and scheduling problem in MPR-based WSNs as an optimization problem and presented a feasible heuristic scheme. For the optimization problem formulation, we firstly derived the necessary and sufficient conditions for interference free link scheduling, which is also used for the design of feasible heuristic scheme. We then relax these necessary and sufficient conditions into a linear form, the necessary conditions. Based on these necessary conditions, the optimization problem is formulated. The issued heuristic algorithm consists three steps. The first step – routing step, is finished by the formulated linear programming. The second step is to find a link schedule using a greedy algorithm. We assign time fraction to the found link schedule by formulating another linear program. The experimental results showed that the MPR ability can bring

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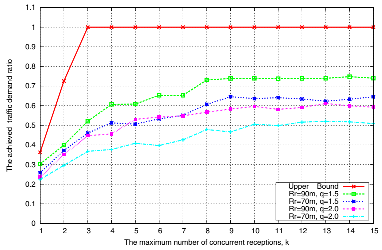

Fig. 1. The achieved traffic demand ratio vs k, sink is 47

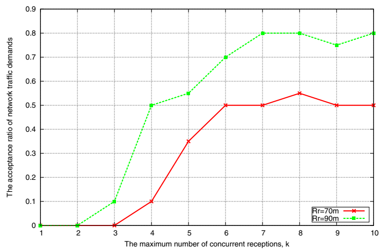

Fig. 2. The acceptance ratio of network traffic demands vs k, sink is 47

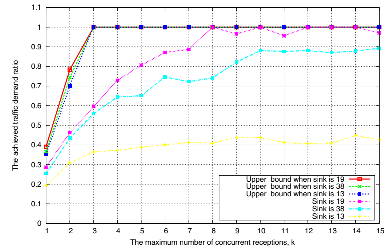

Fig. 3. The achieved traffic demand ratio vs k, $R_r = 90m$

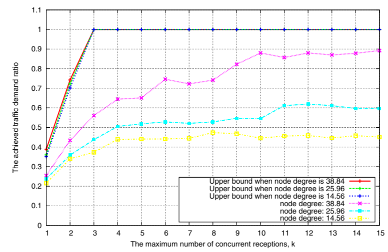

Fig. 4. The achieved traffic demand ratio vs k, sink is 38

notable throughput gain and the network parameters such as network connectivity, sink node placement impact the network throughput notably.

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