A Proportional Fair Backoff Scheme for Wireless Sensor Networks

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***Abstract*—This paper aims at improving the throughput of the wireless sensor networks (WSNs), particularly to overcome the so-called funneling effect for WSNs with converge-cast patterns. Due to the disproportionate larger number of packets accumulated in the sensors that are closer to the sink, there is a need to decrease the collisions and increase the throughput around the sink area as well as the nodes that experience a heavy pass-through traffic. In this paper, we proposed a new scheme, namely PFB (Proportional Fairness Backoff), which provides additional scheduling opportunities to nodes closer to the sink. The new scheme employs Kelly's shadow price theory to achieve the proportional fairness, which takes advantage of the tree topology that is the de facto standard in today's WSNs. In PFB, the size of backoff window is dynamically adjusted with respect to the height of nodes belong in the tree. With close-form analysis and extensive simulations, we show that PFB can achieve up to 100% throughput increase over the widely used CSMA when the network is highly loaded.**

***Index Terms*—Backoff, Proportional fairness, Shadow price, Wireless sensor networks**

I. Introduction

Wireless sensor networks (WSNs) have received significant attention over the last few years. Medium Access Control, which decides the use pattern of the wireless channels, plays the important role in the WSNs data link layer. Consequently, common method for multiple access control is designed as CSMA (carrier sensor multiple access). The CSMA method has a lower delay and promising throughput potential at lower traffic loads, which mainly includes two kinds of protocols: CSMA/CD (Carrier Sense Multiple Access / Collision Detection) and CSMA/CA (Carrier Sense Multiple Access / Collision Avoidance). However, because normal small sensor nodes lack the mechanism of collision detection, most WSNs can only use CSMA/CA for MAC layer, which has a number of challenging design issues, e.g., 1) low power communication, 2) effective collision avoidance, 3) high data producing rates, and 4) large throughput of transmission.

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As WSNs are generally used for gathering environment information in many applications, e.g., video surveillance based multimedia WSN, enhancing the throughput of WSN to gather more sensory data in the base station is a critical research issue and essentially necessary. However, the unexpected converge-cast patterns [1] will engender the funneling effect [2], which can drastically affect the WSNs throughput and the volume of gathered sensory data in the base station.

In order to successfully solve the identified research problem and increase the throughput of WSN, in this paper, we propose a new Proportional Fair Backoff scheme (PFB) for WSNs. In PFB, first, we calculate shadow price [3] that is related to the height of WSNs tree. Then we use the calculated shadow price to get the backoff windows size [4] to achieve the proportional fairness [5] in WSNs. Ultimately, we use the windows to back off. The basic idea of our approach is that we mitigate the funneling effect so as to improve the throughput of WSNs by enhancing the MAC protocol.

The remaining part of this paper is organized as follows: In section 2, the related work is briefly surveyed. Section 3 presents the funneling-tree structure and funneling effect situation. The PFB scheme is proposed in Section 4. Section 5 gives the simulation results and performance analysis, and Section 6 concludes this paper.

II. Related Work

Many related research work on the performances of MAC protocols have been conducted, and can mainly be categorized into two classes: 1) MAC protocols that use general methods to obtain high performance, and 2) fairness MAC protocols.

MAC protocols that use general methods to obtain high-performance. In [6], the authors propose S-MAC protocol with several advanced features: 1) long messages are divided into frames and sent in a burst, and 2) energy conservation, because S-MAC uses periodic active/sleep strategy. However, the S-MAC method also has some drawbacks: 1) broadcast data packets do not use RTS/CTS mechanism [7], which increases the probability of collision; 2) nodes must incur a certain amount of overhead in order to maintain their synchronized wakeup time. Another protocol T-MAC [8] is similar to the S-MAC protocol and both of them are scheduled contention protocols. DMAC protocol [9] proposes to deliver data along the data gathering tree, because the data delivery paths from multiple sources to the sink are in a tree structure, aiming at both energy efficiency and low latency. In [10], Enz et al. proposed the Wise-MAC protocol with the characteristic that it owns two channels: data channel and control channel, and they have different access methods: TDMA and CSMA respectively. Besides Traffic-Adaptive MAC Protocol (TRAMA) [11], the Sift [12] protocol of event-driven and Dynamic Sensor-MAC (DSMAC) [13] are all improved the S-MAC protocol.

Fairness MAC protocols. The fairness at the MAC layer is studied in [14] [15] [16] [17] [18]. Generally, two types of fairness are used frequently, which are 1) proportional fairness and 2) max-min fairness. In [19], the authors introduce an proportional fairness congestion control in FDMA/CDMA networks and this opinion can be used to control the rate, and gain the low-power. The max-min fairness is studied in [20] and [21], in which the research goals were designed for enhancing the max-min fairness, energy efficiency, throughput, and reduces the delay. In paper [22], the authors proposed an adaptive rate control mechanism that achieves fairness while energy efficiency for both low and high duty cycle on sensor nodes. In approach in [23] selects multiple paths for routing to provide a bandwidth allocation in terms of the max-min fairness by using a centralized heuristic algorithm. In 2006, Chen proposes a new aggregate fairness model [24]. This paper proposes a new aggregate fairness model and a localized algorithm which automatically and fairly adjusts a sensor's forwarding rate to avoid packet drops caused by downstream congestion, in order to improve energy efficiency. In [25], V. Gambiroza *et al*. put forward the TAP fairness in multihop wireless backhaul networks.

In summary, to the best of our knowledge, almost all of existing research work mainly considered the balance between energy efficiency and fairness on MAC layer, and did not optimize the fairness to solve the throughput problem of WSNs. As the distinctive features of this research work, we utilize the shadow price to gain fairness first, then we use suitable backoff windows for every sensor node and avoid the energy wasting at the same time.

III. The Funneling-tree and Funneling Effect

Definition 1 Funneling effect: the funneling effect is defined as the situation in WSNs: a small number of hops loose a disproportionate larger number of packets in the sensors that are the nearest nodes to the sink, and collision is significantly more than sensors that are further away from the sink, hence, decreasing the throughput, shortening the operational lifetime, and breaking the stability, of the overall WSNs, which is illustrated in Fig. 1.

Definition 2 Intensity Region: we define the region of the funnel as the intensity region, as shown in Fig. 1.

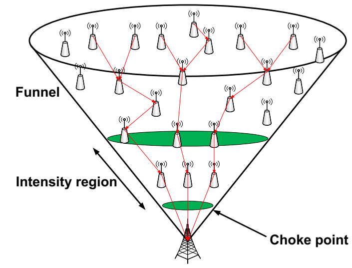

Fig. 1. Funneling Effect and Intensity Region

Definition 3 Proportional fairness: the proportional fairness is defined as: based upon maintaining a balance between two competing interests, trying to maximize total WSNs throughput while at the same time allowing all users at least a minimal level of service, and this is done by assigning each data flow a data rate or a scheduling priority (depending on the implementation).

In [26], the authors conjecture that by putting additional control on the first few or more hops from the sink they can significantly improve the communication performance and eradicate the funneling effect. This method is called funneling-MAC. Because it has different operates in different regions, the control of this method is complex. The funneling-MAC mitigates the funneling effect by using local TDMA (hybrid TDMA/CSMA) scheduling in the intensity region only providing additional scheduling opportunities to nodes closed to the sink, and other nodes which are far away from the sink use pure CSMA. Because of this demerit of funneling-MAC, we propose a scheme that uses global Proportional Fairness strategy to gain appropriate windows' size of backoff for every node, in order to avoid larger number of packets and decrease collision in the sensor nodes which are in the intensity region, in the end increase the throughput of whole networks.

IV. Proportional Fair Backoff (PFB) Scheme

A. Basic Idea of PFB Scheme

The basic idea is that we use a shadow price to allocate the backoff windows, and then according to the size of the backoff windows, we control the transmission rate of forwarding nodes. Because of the funneling effect, sensor nodes that are in the intensive region need more channel access opportunities. Thus, the height of the sensor node in the WSN tree serves as an important parameter in our scheme, which allows us to allocate the size of backoff windows. In the other words, different height of the sensor node in the WSN tree means different window size and different transmission rate. Ultimately, we can achieve the goal of proportional fairness.

In [3], Kelly utilized the utility functions of users to reach the optimum solution of the system. First we can gain utility functions of system, $SYSTEM(U, A, c)$:

$$\max \sum_{r} U_r(x_r), Ax \leq c, x \geq 0.$$

$U_r(x_r)$ is utility function of user r, and x_r is sum of flow that user r has been assigned. A is the adjacency matrix (if $j \in r$, $A[j,r]=1$).

Second the Lagrangian of the $SYSTEM(U,A,c)$ problem:

$$L_s = \sum_r U_r(x_r) - \sum_j \mu_j(\sum_{r:j\in r} x_r - c_j).$$

Because the utilities are unlikely to be known by the network, Kelly only can consider two simpler problems: $USER$ problem and $NETWORK$ problem.

According to the Lagrangian of the $SYSTEM(U,A,c)$ problem, we can gain the KKT conditions:

$$\frac{\partial L_s}{\partial x_r} = U_r^{'}(x_r) - \lambda_r = 0, \lambda_r = \Sigma_{j:j\in r}\mu_j, \forall r, \tag{1}$$

$$Ax \le c, \tag{2}$$

$$x \ge 0, \mu_j \ge 0, \tag{3}$$

$$\mu_j(\sum_{r:j\in r} x_r - c_j) = 0, \forall j. \tag{4}$$

Kelly found that formula 1 only depends on U_r and λ_r. The formula 1 is only related to user, so this part is $USER$ problem and formula 4 is $NETWORK$ problem. Kelly used utility maximization to describe $USER$ problem and $NETWORK$ problem, $USER(U_r, \lambda_r)$:

$$\max U_r(x_r) - \lambda_r x_r, x_r = \frac{\omega_r}{\lambda_r}, x_r \ge 0,$$

and $NETWORK(A,c,\omega)$:

$$\max \sum \omega_r \log x_r, x_r = \frac{\omega_r}{\lambda_r}, Ax \le c, x_r \ge 0, \forall r.$$

Note that λ_r is shadow price, and the shadow price is a value change that is obtained by relaxing the constraint. The shadow price can provide decision-making of optimization problems. Kelly deemed that shadow price can be used to optimize the network, and Kelly's paper advanced that a system optimum is achieved when users' choices of charges and the network's choices of allocated rates are in equilibrium. λ_r is related to x_r, so we can set λ_r=$\sum_{j:j\in r} f_j(\sum_{r:r\in j} x_r)$, and in this paper we chose appropriate f to design shadow price.

Then in [27], Kelly analyzes the stability and fairness of two classes of rate control algorithms for communication networks, and these two classes of rate control algorithms are all involved with shadow prices.

We use the shadow price to determine the windows' size, and this price is related with height of tree topology.

We define our shadow price as follows, and this price is involved with height:

$$p(y_r, N) = \Sigma_{j=1}^{N} \frac{[y_r - \frac{c_j}{N}]^+}{y_r}, N = 2^h, \tag{5}$$

subject to

$$y_r = \sum x_r.$$

In this formula, p is shadow price that is defined by height of tree, and h describes the node's height. Consider a network with a set of links L such that link l$\in L$ has capacity C_j and x_r is transmission rate of son nodes and y_r is receipt rate of father node. And in Fig. 2 we show the parameter setting.

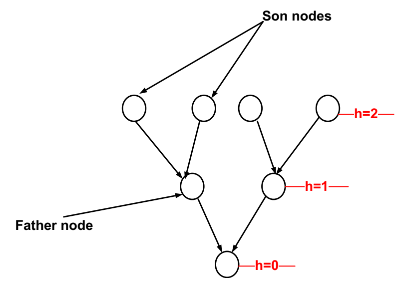

Fig. 2. Schematic of Parameter Setting

In this section, we introduce the process of backoff.

- If the channel is idle for a period of time which equals to the DCF IFS (DIFS), the sensor node can begin transmission.
- If the channel is busy and the transmission is deferred, the node must backoff. A backoff interval (BI) is randomly selected between zero and a contention window period ($CW(h)$), we can define the $CWmin$:

  $$CWmin = 2^i - 1,$$

  when i=5, we can get the value of $CWmin$=31, then according to the $CWmin$, we can get the $CW(h)$ of every layer:

  $$CW(h) = p(h) \times CWmin.$$

- A collision occurs if two or more nodes select the same BI, which can happen when a large number of nodes contend for the channel. To reduce the probability of collision, the CW is doubled every time when a collision occurs until $CWmax$ is reached, and the $CWmax$=1023, the CW is

  $$CWnext = 2^i - 1 (i = 6, 7, 8, 9, 10),$$

  and

  $$CW(h) = p(h) \times CWnext.$$

- BI is calculated as follows:

  $$BI(h) = Random(0, CW(h)) \times SlotTime.$$

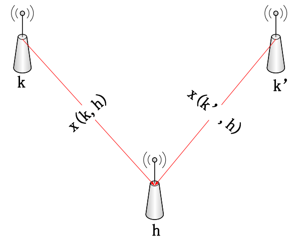

Fig. 3. The Structure of Condition 1

B. The Proof of Maximal Proportional Fairness

A feasible rate assignment is said to achieve the proportional fairness if it satisfies the condition 1: the weighted mean rate $x_{k,h}$, k is upstream neighbor, cannot be increased without decreasing the weighted mean rate $x_{k',h}$ which is the rate of another upstream link (k', h), Fig. 3 expresses the structure of condition 1:

About the proportional fairness, it is based upon maintaining a balance between two competing interests. Proportional fairness means maximize the total throughput of wireless sensor network while at the same time allowing all users at least a minimal level of service. Proportional fairness takes a balanced position.

According to the condition 1, we define the theorem 1 and proof it in the next step.

Theorem 1. After PFB scheme sets the backoff windows at all sensor nodes, and at the same time the rates are assigned to every node, the resulting rate assignment on the whole network achieves the maximum and proportional fairness.

Proof: Consider an instability node h. Let be the set of upstream neighbors, $x_h$is the rate of node h, $p_{k,h}$is the number of packets in the link (k, h), and $\forall k \epsilon U_i$. According to the condition 1, if we increase $x_{k,h}$, $x_{k',h}$ which is the rate of another upstream neighbor k' must be decreased, in order for the combined rates from all upstream neighbors remain the rate of node h. At first, we get the fair backoff windows from our scheme, and then we can find relation of among the rates. We suppose the rate which was calculated by PFB scheme:

$$x_k = \frac{p_{k,h}}{\sum_{j\epsilon U_i} p_{j,h}} \times x_h, \forall k \epsilon U_i, \tag{6}$$

and

$$x_{k'} = \frac{p_{k',h}}{\sum_{j\epsilon U_i} p_{j,h}} \times x_h, \forall k' \epsilon U_i. \tag{7}$$

then we suppose upstream neighbor rates that are not calculated in accordance with PFB scheme.

$$x'_k = \frac{p_{k,h}+1}{\sum_{j\epsilon U_i} p_{j,h}} \times x_h, \forall k \epsilon U_i, \tag{8}$$

and

$$x'_{k'} = \frac{p_{k',h}-1}{\sum_{j\epsilon U_i} p_{j,h}} \times x_h, \forall k' \epsilon U_i. \tag{9}$$

According to the condition 1, we get two equations:

$$x_k + x_{k'} = x_h, \tag{10}$$

$$x'_k + x'_{k'} = x_h. \tag{11}$$

then we deduce another two equations:

$$x_k = x_h - x_{k'}, \tag{12}$$

$$x'_k = x_h - x'_{k'}. \tag{13}$$

1) If $x'_k > x_k$ and $x'_{k'} > x_{k'}$, by 12 and 13, $x_h - x'_{k'} > x_h - x_{k'}$ then $x_{k'} > x'_{k'}$, this conclusion is contradictory to hypothesis, therefore the hypothesis is false.
2) If $x'_k < x_k$ and $x'_{k'} > x_{k'}$, by 6 and 8, like: $(\frac{p_{k,h}}{\sum_{j\epsilon U_i} p_{j,h}} \times x_h) > (\frac{p_{k,h}+1}{\sum_{j\epsilon U_j} p_{j,h}} \times x_h)$, then $(p_{k,h}+1) < p_{k,h}$, this is a false equation.
   By 9 and 7, $(\frac{p_{k',h}-1}{\sum_{j\epsilon U_i} p_{j,h}} \times x_h) > (\frac{p_{k',h}}{\sum_{j\epsilon U_i} p_{j,h}} \times x_h)$ then $(p_{k',h}-1) > p_{k',h}$, this is also a false equation, therefore the hypothesis is false.
3) If $x'_k > x_k$ and $x'_{k'} < x_{k'}$, then $x'_k + x_{k'} > x_k + x'_{k'}$, further $x'_k - x'_{k'} > x_k - x_{k'}$. In this inequality, the meanings of $-(x'_{k'})$ is the reverse rate of k': $x'_{k'}$, but the values are equal, the values $-(x_{k'})$ and $x_{k'}$ are also equal, that is, $x'_k + x'_{k'} > x_k + x_{k'}$. By 10 and 11, $x_h > x_h$, but this is not an inequality. Therefore the hypothesis is false.

According to these three false hypothesizes, we can deduce two appropriate inequalities: $x_{k'} > x'_{k'}$ and $x_k > x'_k$, which are the largest weighted mean rates among all upstream neighbors, and the rates which are calculated by PFB scheme are maximal proportional fairness rates.

V. Performance Evaluation

In this section we introduce simulation experiment, and then according to the results we analyze the performance of throughput.

A. Simulation Setup

In order to show our scheme is effective in the aspect of throughput, we use the CSMA/CA compared with our PFB scheme. We expect the performance to be improved in throughput using PFB scheme. The two schemes are implemented in ns-2 network simulator. According to the two schemes, each node independently picks the neighbor node within its transmission range to transmit data. Namely, we need effective way to back off in order to maintain the circulation of network traffic when network is busy, such as funneling effect. In order to guarantee every node can find its neighbor node at any time, we choose the static routing protocol (NOAH), and the topological structure is full binary tree structure. In the simulation, there are 31 static nodes which are distributed in 5 layers. Every child node transmits data to its father node within its transmission range with equal probability, according to the static protocol (NOAH). The CBR network flow generator is based on the UDP protocol. The main simulation parameters are showed in the Table 1.

TABLE I
SIMULATION PARAMETERS

Parameters	Parameter values
Number of nodes	31
CBR start time/s	1
CBR stop time/s	200
CBR frame size/byte	1000
WirelessPhy bandwidth/Mbps	2

B. Throughput Analysis

In order to analyze throughput in more detail, we implemented these simulation experiments with different rates ranging from 100kbps to 900kbps, and the goal is to gradually drive the network from low to moderate load and then into a congested and saturated state. Fig. 4 shows the various different data rates and the corresponding throughput performance measured at the sink where all the 30 nodes are sources.

We can clearly see that in CSMA/CA the throughput at the sink rises to a peak approximately 184kbps before the network falls into congested and saturated state. Further increase in data rate only drives the network into further overload, while PFB has an increase in throughput as the data rate increases. We observe from Fig. 4 that data rates of 100kbps, 200kbps, and 800kbps represent light, medium, and overload traffic scenarios respectively, then Fig. 5, Fig. 6 and Fig. 7 show the trace of the throughput about the PFB and CSMA/CA with data rates of 100kbps, 200kbps, and 800kbps.

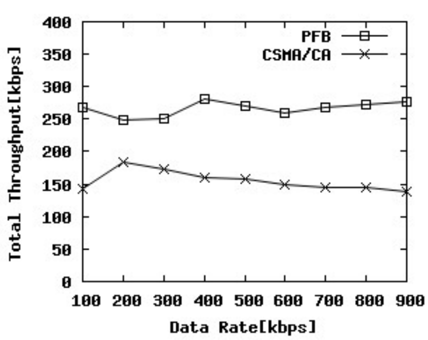

Fig. 4. Throughput Comparison with Varying Data Rate

The reason of packet loss for light and medium traffic scenarios is collision and hidden terminal problem, while in the high and overloaded traffic scenarios loss is mainly due to buffer overflow in addition to collision and hidden terminal problem. These results indicate that controlling the size of the contention window in the network could mitigate buffer overflow to offer significant gains across all data rates considered in the experiment. We note that PFB outperforms CSMA/CA consistently over all data rates considered in the experiment.

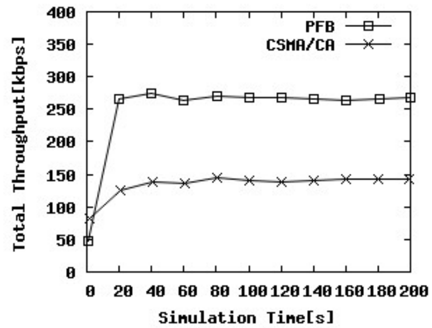

Fig. 5. Trace of Throughput with Data Rate of 100kbps

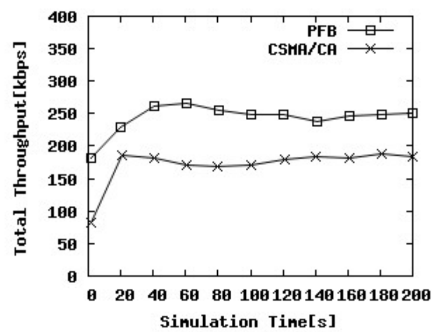

Fig. 6. Trace of Throughput with Data Rate of 200kbps

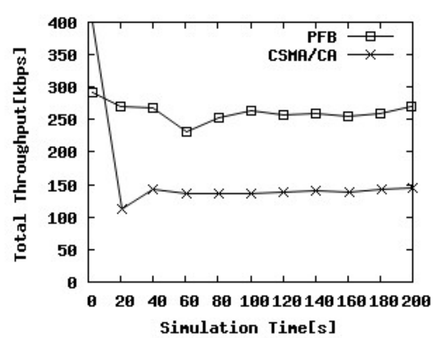

Fig. 7. Trace of Throughput with Data Rate of 800kbps

VI. Conclusion

In this paper, we proposed a scheme for collision resolution in a CSMA protocol, and namely we used the price control to resolve collisions by backing off. In order to improve performance of the basic protocol under dense or active network conditions, we combined our PFB scheme in CSMA protocol, CSMA/PFB, and we call this new method is PFB scheme. Simulation results of PFB scheme outperform IEEE 802.11 CSMA/CA in throughput. Analyzing the executive mode of our scheme in medium access control, we observed that these results are based on a distributed strategy, and we calculated the distributed shadow prices which decide backoff windows to each layer. This suggests that an investigation of CSMA with a distributed protocol is warranted. More study is needed about fairness for WSNs. For example, we can use fairness strategy to solve the problem of save energy, and as we know that energy is very important in WSNs.

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