CONCURRENCY AND COMPUTATION: PRACTICE AND EXPERIENCE
Concurrency Computat.: Pract. Exper. 2013; **25**:112–128
Published online 23 April 2012 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/cpe.2843

SPECIAL ISSUE PAPER

A backoff differentiation scheme for contention resolution in wireless converge-cast networks

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SUMMARY

Wireless converge-cast networks (WCNs), such as data collection-based wireless sensor networks, exhibit certain phenomena called funneling effect, where the region close to the sink node is heavily overloaded. In this paper, we identify that the funneling effect occurs not only close to the sink but also within the network region where nodes have collision and induce heavy traffic to relay; we name it hot-spot funneling effect. This paper aims to improve the throughput and fairness of WCNs by mitigating the micro funneling effect. We propose a new mechanism, the backoff differentiation for contention resolution (BDCR), which is targeted to a system-wide high throughput on the basis of the contention resolution mechanism. To achieve high spatial reuses, BDCR divides the network into several regions and does backoff differentiation within each region. Within each backoff differentiation region, the backoff window range is adjusted according to the traffic rate, and at the same time, the backoff values are set with the awareness of the traffic intensity level. All regions share the same algorithm, which uses Kelly's rate control theory and method to allow each sensor to locally adjust its backoff value. One of the key advantages of BDCR is that it is extremely easy to implement. With extensive simulations and testbed experiments, BDCR is proved to achieve much higher throughput over the traditional carrier sense multiple access and some recent media access control protocols in literature, particularly when the network suffers intensive congestions. Copyright © 2012 John Wiley & Sons, Ltd.

Received 22 December 2011; Revised 21 February 2012; Accepted 2 March 2012

KEY WORDS: CSMA; proportional fairness; contention resolution; backoff differentiation

1. INTRODUCTION

Wireless sensor networks (WSNs) are rapidly becoming pervasive in human's life for diverse applications, which also introduce many challenging issues. In practice, existing WSNs are not able to use the limited bandwidth fully. Literatures, for example, [1], claim the research problem that the bandwidth utilization rate for scientific monitoring in WSNs is still very low, that is, less than 1000 bytes per second for transmission. However, some applications, for example [2, 3], actually demand higher data transmission rate, which motivates the essential research effort in this paper for improving the throughput of WSNs with better bandwidth utilization rate.

Congestion is always one of the major issues that affects the WSNs throughput. There are many reasons underlying this fact, for example, the inefficient scheduling and control in media access control (MAC) layer or poor designed routing protocols in network layer [4]. In this paper, we want to highlight the so-called funneling effect [5], which is a natural product of many-to-one

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communication pattern or converge-cast namely. Funneling effect means that the region closing to the sink of a WSN is often in a high congestion status because of the aggregation on the traffic from all the sensor nodes down to the sink node.

With a further investigation on the funneling effect, it is discovered that the funneling effect occurs not only in the region closed to the sink but also in any area where nodes have a large amount of traffic to relay, again because of the many-to-one communication pattern. Furthermore, we use 'micro funneling effect' to describe each subregion funneling effect.

The funneling effect implies a serious fairness problem: if all nodes, including nodes in intensive area and other nodes in normal scattered area, have a uniform channel access opportunity, then it is unfair for the nodes that always have more traffic to relay. Thus, to address this issue, we need one distributed scheme to allow each node to locally adjust its channel access opportunity. Backoff differentiation (BD) [6] is undoubtedly a good candidate, particularly for carrier sense multiple access (CSMA)-like protocols. Nodes are assigned a fair access opportunity to mitigate the link conflict [7]. BD is defined as using different backoff window spans for different nodes, for instance, two neighbor nodes may have different minimal or/and maximal backoff window sizes according to their various data transmission requirements (traffic load).

Our main goal in this paper is to mitigate the micro funneling effect via contention resolution, whereby to improve the overall network throughput. To achieve this goal, our method divides the whole network into certain number of 'regions', then eliminates the micro funneling effect within each region, which can help increase the spatial reuse. One crucial open problem is that how to identify these 'micro' funneling areas as shown in Figure 1. The natural attempt to solve the problem is by investigating the interference properties [8] because when an area is highly loaded or in severe contention, the interference will become very strong because of the openness of wireless medium. Thus, we try to build a model of the funneling effect with the conflict graph and propose a region partitioning method to divide the whole system into different regions based on the conflict graph techniques [9, 10].

Within each region, we use a method of BD, namely proportional fairness backoff (PFB) scheme to mitigate the micro funneling effect. Specifically, each node uses PFB scheme to adjust its backoff window with respect to their traffic load to the sink node, which is along the data streaming path. The more traffic load, the smaller window size it should have, consequently, the more channel access opportunities the node has. Ultimately, the whole network achieves the goal for optimizing the overall throughput.

By observing the communication pattern of a global fairness of channel access and WSNs, we obtain one insight, which we call 'flow directional-ness': The nodes exhibit strong correlations in terms of the positions (the distance to the sink node) along the data stream, such as downstream, from a sensor node to the sink node. For instance, the upper level nodes (closer to the sink node) normally have more traffic to deliver than lower level nodes have (far away from the sink node than upper nodes). We will take advantage of this property to facilitate our work.

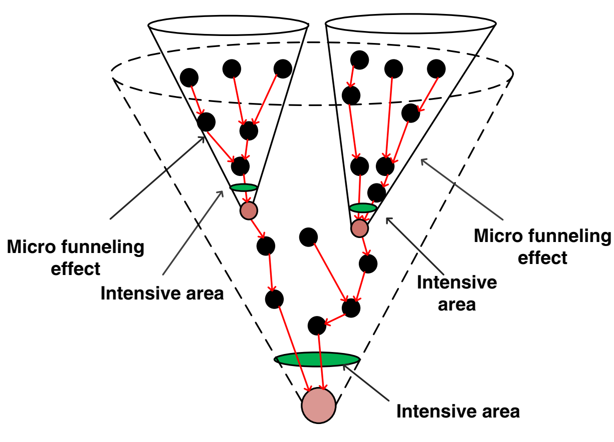


Figure 1. Micro funneling effect in sensor networks.

DOI: 10.1002/cpe

The contributions of this paper are summarized as follows: (i) Interference-aware Region Partitioning: With the conflict graph techniques and the interference models, we designed a centralized algorithm as well as a distributed one to do the region partitioning whereby the spatial reuse is exploited effectively; (ii) Fairness: Within the BD region, Kelly's rate control method [11] is applied to achieve the proportional fairness. We proved that our backoff adjustment algorithm satisfies proportional fairness [11]; (iii) Backoff Differentiation: We proposed a BD scheme, where different nodes may have different backoff window spans with respect to the traffic levels, whereas in traditional WSNs, the backoff window span of each node is set homogeneously (same order of window spans); (iv) A Solution with Flexibility: The proposed scheme has extremely good compatibility that can be implemented in CSMA-like protocols. In comparison with time division multiple access (TDMA) scheduling, it does not require complex time synchronization and coordination but adjusts the backoff value, which is scalability and applied to the scale to large networks.

This paper is organized as follows. Section 2 investigates related work of MAC protocols in WSNs. Section 3 describes the models and problem formulation. Then, we present the proposed centralized algorithm as well as the distributed algorithm for backoff differentiation for contention resolution (BDCR) region partitioning in Section 4. The BD within a region is proposed in Section 5. Section 6 shows the simulation and testbed experiment results. We conclude this paper in Section 7.

2. RELATED WORK

Aiming at the contention resolution, we classify the related work into the following categories: (i) Backoff Optimization; (ii) MAC Fairness; and (iii) Funneling Effect.

1) Backoff optimization: Backoff is one of the major contention resolution techniques in medium access, where a contention window (CW) is often used, and it is widely implemented in wireless networks. The standard backoff algorithm in the IEEE 802.11 distributed coordination function (DCF) is the binary exponential backoff. But binary exponential backoff is not completely fair. It is always in favor for the nodes that transmit data successful in a short time. To improve the contention resolution, there are plenty of work on backoff optimization algorithms, which may be categorized into two kinds: (i) Improving on the CW update mechanism: Multiplicative increase linear decrease [12] specifies that CW is α times the previous value when the transmission fails, and CW reduces a constant β when the transmission succeeds, and it is applicable for the networks with a small number of nodes. Dynamic backoff algorithms with respect to the network state: P-MAC [13] adjusts a optimum CW with respect to the network states and the weights of the flows. (ii) Dynamic adjustment based on priorities: Fast Collision Resolution [14] increases the CW of the potential contention nodes before collisions to reduce the possibility of collisions and improve the throughput of the network. Most of the backoff optimization work are discussed in the regime of wireless local area network. These techniques cannot be applied directly to WSNs because of their unique characteristics such as limited computational power and memory size.

2) Fairness: Nandagopal presents a general mechanism for translating a given fairness model into a corresponding contention resolution algorithm in [15]. According to a randomly generated topology, the author obtains a flow conflict graph to show the contention among flows and a resource constraint graph to show relationship between the distinct contention region in flow contention graph and flows. Given a resource constraint graph, he found that the fairness model of the system is determined by a utility function that must be maximized. The issue of the fairness is a per-node fairness not for global and not converge cast. The protocol is implicitly able to provide only per-node fairness, and falls apart asymmetric contention neighborhoods, which is unlike Mutiple Access, Collision Avoidance protocol for WLAN (MACAW) and BC-Fair that achieve a per-flow fairness through using per-flow queues with per-flow backoffs.

Kelly presents a tractable mathematical model and uses it to analyze the stability and fairness of a class of rate control algorithms [11]. He proposes a simple rate control algorithms using additive increase/multiplicative decrease rules or explicit rates on the basis of resource shadow price, which

DOI: 10.1002/cpe

reaches stable convergence and achieve proportional fairness. And the network's implicit objective provides a Lyapunov function for the dynamical system defined by the rate control algorithm. Kelly proposed two classes of algorithms, primal algorithm and dual algorithm, which may be generalized to including routing control and provide natural implementation of proportionally fair pricing to solve the network's optimization problem.

3) Funneling effect: Funneling effect is proposed in [16]. It means that the sensors near the sink node relay most of the data, and most easily occur collisions with the large data transmission requirement where data packet generated under varying workload and moved quickly toward one or more sink nodes. To migrate the problem, a localized, sink-oriented funneling-MAC was proposed in [5]. All sensors apply pure CSMA/CA by default, but if they receive a beacon from the sink, they will consider themselves to be in the intensity region and perform TDMA instead. To enhance the robustness and flexibility of the funneling-MAC, a CSMA frame is reserved between two consecutive TDMA frame schedules, and even the scheduled transmission also performs carrier sensing. Actually, there is a simple hybrid TDMA/CSMA scheme implemented in the intensity region under the control of the sink, which can improve the throughput and loss performance of WSNs under varying network load.

4) MAC protocols: In recent years, many special MAC protocols in WSN have been proposed; these protocols can mainly be divided into three categories: contention-based, TDMA-based, and CSMA/TDMA-based hybrid MAC protocols [17]. In contention-based protocol, such as S-MAC [18], B-MAC [19], PMAC [20] and T-MAC [21], nodes can transmit without having any predetermined time assigned to them. When the nodes need to send data, they use wireless channel through carrier sense and competitive access. Therefore, there are unwanted collision. These protocols provide mechanisms for avoiding and resolving collisions. Fusion [22] uses queue length to measure levels of congestion and when a congestion is detected, it applied a hop-by-hop backpressure strategy to regulate the data rate of the sources. Congestion Detection nd Avoidance (CODA) [23] measures both the channel and buffer to detect congestion. Other than open loop backpressure, CODA also adopts an end-to-end acknowledgement strategy to deal with consistent congestion. In the TDMA mode, each node has its own proprietary slot to get access the channel, which can avoid carrier sense in the competitive access. In addition, there are still some disadvantages. It needs time synchronization that is difficult to implement. It is a challenge to optimally allocate a collision-free time slot to each node in a dynamic network. Ttraffic-Adaptive Medium Access Protocol TRAMA [24], a TDMA-based protocol, ensures nodes collision-free communication based on actual traffic when using pre-assigned time slots. And the nodes that have no communication go to sleep to reduce energy consumption caused by collision and idle listening. And it demands nodes more energy, storage space, and computing ability to keep clock synchronization and scheduling alternate access, which is difficult for sensor nodes. TreeMAC [25] is a localized TDMA MAC protocol, which divides a time cycle into frames and each frame into slots. A parent node determines the children's frame assignment based on their relative bandwidth demand, and each node calculate its own slot assignment based on its hop-count to the sink. On the basis of advantages and disadvantages of CSMA and TDMA, some hybrid MAC protocols that are based on CSMA and TDMA have been proposed. The Funneling-MAC protocol [5] is a typical one. Z-MAC [26] is another typical CSMA/TDMA-based hybrid MAC protocol. When the flow is low, it uses CSMA to improve channel utilization and reduce latency. When the network is crowded, it uses TDMA to reduce collision and crosstalk. Abbaspour *et al*. proposed an adaptive CSMA/TDMA hybrid MAC protocol based on IEEE 802.15.4 standard [27]. It involves two parameter to determine the border between CSMA and TDMA: channel utilization level in CAP and the amount of pending data in nodes' queues.

3. MODELS AND PROBLEM FORMULATION

3.1. Network model

We assume that there are a set of sensor nodes deployed in a plane. Each node is only equipped with a single radio interface. The communication graph $C = (S, E)$ is directly derived from the WSN

DOI: 10.1002/cpe

topology, where $S = \{s_1, s_2, \dots, s_n\}$ is the set of nodes and E is the set of possible communication links. Each node has a transmission radius of t_i so the necessary condition for a successful communication between nodes s_i and s_j is $\|s_i - s_j\| \leqslant t_i$, where $\|s_i - s_j\|$ is the Euclidean distance between s_i and s_j. Notice that $\|s_i - s_j\| \leqslant t_i$ is not the sufficient condition for $(s_i, s_j) \in E$ because there will be other factors affecting the transmission between two nodes such as the physical barriers and the selection of routing protocol. If there is $(s_i, s_j) \in E$, we use $l_{i,j}$ to denote (s_i, s_j). Each node s_i also has an interference radius of r_i. Node s_j is interfered by the signal from s_i, if $\|s_i - s_j\| \leqslant r_i$ and s_j is not the intended receiver. Let I_i be the interference region that centers at s_i with the interference radius r_i. Here, the interference radius r_i is not necessarily to be the same as the transmission radius t_i. Instead, typically, the interference radius is larger than the transmission radius. Let $\gamma_i = \frac{r_i}{t_i}$ be the interference-transmission ratio for a node s_i, and in practice, $2 \leqslant \gamma_i \leqslant 4$.

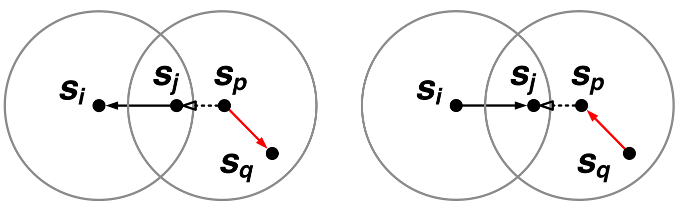
3.2. *Interference model*

In this paper, we focus on the interferences caused by request to send/clear to send (RTS/CTS), namely the RTS/CTS model, which has been prior studied in [28]. Under the RTS/CTS model, for each pair of a transmitter and a receiver, the nodes within the interference region of the transmitter will be restrained by RTS as Figure 2(a) shows. Nodes within the interference region of the receiver will be restrained by CTS as Figure 2(b) shows. Thus, for each pair of simultaneous transmission links, say $l_{i,j}$ and $l_{p,q}$, they should satisfy that (i) they are four distinct nodes, that is, $s_i \neq s_j \neq s_p \neq s_q$; (ii) s_i and s_j are not in the interference regions of s_p and s_q, and vice versa. Let $I_{i,j}$ be the interference region of a link $l_{i,j}$, and it is the union of the interference regions I_i and I_j. When a directed link $l_{i,j}$ (or $l_{j,i}$) is active, a link is restrained if any node of its nodes is in $I_{i,j}$. Furthermore, though neither s_p nor s_q is in $I_{i,j}$, $l_{i,j}$ still interferes with $l_{p,q}$ because s_i or s_j may be inside $I_{p,q}$.

3.3. *Conflict graph model*

Conflict graph has been used as a handy tool to analyze interference models. There are generally two kinds of conflict graph used to describe the interferences in a real wireless network: the link conflict graph [9] and the node conflict graph [10]. As shown in Figure 3(b), for a link conflict graph, each vertex corresponds to a link in the communication graph. There is an edge between two vertices if the corresponding two links cannot transmit simultaneously under the interference model. In the node conflict graph, as shown in Figure 3(c), each vertex corresponds to a node in the communication graph. There are the directed edges from s_i to s_p and to s_q if a link $l_{p,q}$ is interfered by RTS of the node s_i. Similarly, there are the directed edges from s_p and s_q to s_j if the link $l_{p,q}$ is interfered by CTS of the node s_j.

This paper focuses on the interference under the RTS/CTS model. Let F_C be the link conflict graph and N_C be the node conflict graph under RTS/CTS, respectively. Our objectives are to divide the nodes into serval BD regions, then assign an appropriate backoff value to each node to achieve the better throughput and fairness all over the network. To achieve the objectives, we need to design algorithms from two aspects: BD region partitioning and an appropriate backoff value. We use the



(a) Restrained by RTS (b) Restrained by CTS

Figure 2. Communication restriction by RTS/CTS. (a) This shows the case that communications from s_j to s_i and from s_p to s_q cannot take place simultaneously because of RTS. (b) This shows the case that communications from s_i to s_j and s_q to s_p cannot take place simultaneously because of CTS.

DOI: 10.1002/cpe

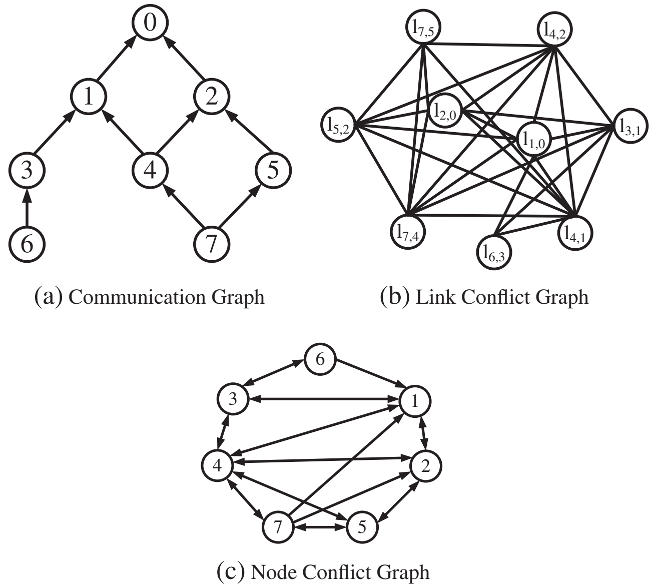


Figure 3. An example of conflict graph. (a) Communication graph; (b) link conflict graph; and (c) node conflict graph.

node coloring algorithm in the graph theory to resolve the region partitioning. The backoff values of nodes in $R(s_i)$ satisfy that the more load a node has, the smaller backoff value it has.

4. REGION PARTITIONING FOR BACKOFF DIFFERENTIATION

In this section, we propose a centralized algorithm and a distributed algorithm for BD region partitioning under the RTS/CTS model. The performance of the centralized algorithm will be used as a benchmark for evaluating the performance of the distributed algorithm.

4.1. The centralized algorithm

The centralized algorithm processes vertices in an order according to the degrees of vertices in the node conflict graph. The basic idea of region partitioning can be summarized as follows: First, all vertices of the node conflict graph are pushed into a stack in the ascending order of their degrees. A vertex with a smaller degree will be pushed first. If there are more than one vertices sharing a same degree, the vertex with a smaller ID would be pushed first. Then, the vertices pop one by one. Each vertex will be colored by the minimum color ID that is not used by its conflict vertices and be added into the backoff region that all vertices conflict with it. If there is no such region, the vertex will be added into a new backoff region.

First, we present some definitions and properties that are needed to prove the performance of the algorithm. Given a communication link $l_{i,j}$, let $r_{i,j} = \max(r_i, r_j)$ be the interference radius of the link $l_{i,j}$. For a node s_k, let $A(s_k, x)$ be the disk centered at s_k with the radius $x \cdot r_k$. Therefore, the interference region of s_k, I_k, is a particular case of $A(s_k, x)$ when $x = 1$, that is, $A(s_k, 1) = I_k$. Let $S_{i,x}$ be a set of nodes that are in the region $A(s_i, x)$. Let $U(s_k, \alpha)$ be the set of nodes satisfying that (i) each of their interference radius is at least r_k and (ii) each of them interferes some nodes in $A(s_k, \alpha)$. Then, a node from $U(s_k, \alpha)$ could be arbitrarily far away from node s_k.

Theorem 1
For a given node s_i, the backoff region $R(s_i)$ with the cardinality $|R(s_i)| \geqslant |S_{i,3}|/49$ if all nodes in the network have a uniform interference radius r.

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ALGORITHM 1. The Centralized Region Partitioning Algorithm

Input: A communication graph $C = (S, E)$
Output: Backoff differentiation regions R
1: Construct the conflict graph N_C.
2: Push the vertices of the graph N_C in a stack S. The vertices that have smaller degree will be pushed first. For the vertices that have the same number of degree, the vertices with smaller ID will be pushed first.
3: **While** S is not empty **do**
4: Pop the top of the stack s_i, mark it with smallest color ID k that is not used by its conflict vertices, and add it into the region R that has no vertex of this color and at least one vertex communicating with it.
5: **If** there is no existing region **or** all regions have the same color with s_i **do**
6: Create a new region R and add s_i into R.

Proof

First, we consider the region $A(s_i, 3)$. Suppose there exist a node s_k that is outside of the region $A(s_i, 3)$. As Figure 4 shows, $||x_0 - x_1|| = ||x_1 - x_2|| = ||x_2 - x_4|| = r$. The node s_i that is on x_0 and s_x is close to x_4. The node s_j, on the x-axis, can communicate with s_i. When $\gamma_i = 1$, obviously, the link $l_{i,j}$ cannot interferes with any node that can communicate with s_x. Similarly, the link $l_{x,y}$ cannot interfere with any node that can communicate with s_i.

Second, we consider the node set $S_{i,3}$. Using a simple area argument, there are at most $\frac{\pi\left(\left(3+\frac{1}{2}\right)r_i\right)^2}{\pi\left(\frac{1}{2}r_i\right)^2} = 49$ disks with radius $\frac{r_i}{2}$ can be placed inside the region $A(s_i, 3)$. Thus, there exists a node set in $S_{i,3}$ with the size at least $|S_{i,3}|/49$ such that each node in the set interferes with each other. □

Theorem 2

For an arbitrary communicate graph C, a node s_i with the maximum degree belongs to the maximum backoff region R that has the maximum number of vertices.

Proof

We consider two different nodes s_i and s_j, respectively. Let δ_i and δ_j be the degrees of nodes s_i and s_j, and $\delta(C)$ is the maximum degree in the communication graph. Without loss of generality, let $\delta_i = \delta(C)$ and $\delta_i \geqslant \delta_j$, that is, $S_{i,1} \geqslant S_{j,1}$.

First, we consider two sets $S_i = U(s_i, \alpha_1)$ and $S_j = U(s_j, \alpha_2)$, and $R(s_i)$ and $R(s_j)$ are the subsets of S_i and S_j, respectively. Any of two nodes in each subset, $R(s_i)$ or $R(s_j)$, interferes with each other. Let $\alpha_1 = \alpha_2$, and we obtain $S_{i,1} \subset S_i$ and $S_{j,1} \subset S_j$. Any node in $S_{i,1}$ or $S_{j,1}$ can introduce another node into S_i or S_j, respectively, so $|S_i| \geqslant |S_j|$.

Second, according to Theorem 1 in [9], the cardinality of $R(s_i)$ and $R(s_j)$ is at least $|S_i|/C_{\alpha_1}$ and $|S_j|/C_{\alpha_2}$, respectively; C_α is a constant and $C_\alpha \leqslant (6\alpha+1)^2+11$. Because $\alpha_1 = \alpha_2$, $|S_i| \geqslant |S_j|$, and $|S_i|/C_{\alpha_1}$ and $|S_j|/C_{\alpha_2}$ have all the nodes that interferes with s_i and s_j, so $R(s_i)$ is the maximum set in which each node interferes with each other in the communication graph C. □

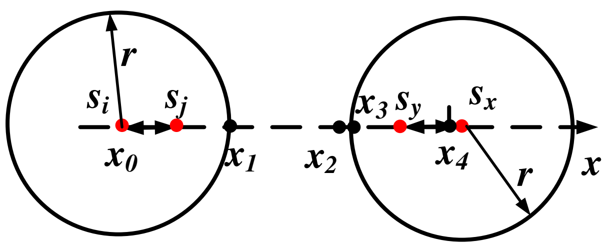

Figure 4. The region of $A(s, 3)$. The distance between s_i and s_x is more than $3r$.

DOI: 10.1002/cpe

Algorithm 2. The Distributed Region Partitioning Algorithm

Input: A communication graph $C = (S, E)$
Output: Backoff differentiation regions $R(s_i)$

Each node s_i collects all communication nodes, say N_i.
Each node s_i finds N^+, which is the subset of nodes in N_i that precedes s_i and let $N_i^- = N_i - N_i^+$.
All nodes in N_i^+ is set uncolored by node s_i.
While some nodes in N_i^+ are uncolored **do**
  Node s_i listens messages from other nodes.
  If s_i receives a message $Color(j, k, r)$ **then**
    Node s_i marks s_j with color ID k and region r if s_j is in N_i^+.
    If there is already node having the color k **then**
      $r_j^u = r + 1$, send the message $Region(j, r_j^u)$ to s_j.
s_i colors itself with the minimum color ID, say k, that is not used by any node in N_i^+.
If the color of s_i is the minimum used color, **do**
  Mark itself with the region $R = \max_{s_j \in N_i^+}\{R_{s_j}\} + 1$,
Else If s_i receives a message $Region(i, r)$ **then**
  Mark itself with the region $R = r$,
Else Mark itself with the region $R = \max_{s_j \in N_i^+}\{R_{s_j}\}$.
Send the message **Color**(i, k, R) to all nodes in N_i^-
If s_i is the sink **then**
  Color itself with the minimum color ID, say k, mark itself with the region R, and send the message **Color**(i, k, R).

4.2. The distributed algorithm

In the distributed algorithm, nodes cannot collect all the information of the network as the centralized algorithm does. So the distributed region partitioning algorithm just relies on the localized information. First, we define some important data structures. Given two nodes s_i and s_j, we say that s_i precedes s_j if $r_i \leqslant r_j$ and $i < j$. Each node will collect its conflict nodes that precedes it in N_i^+, and color itself according to the information of nodes in N_i^+. Each backoff region created by the algorithm has different color nodes.

Lemma 1
In the distributed region partition algorithm, a wireless network can be divided into at least $\left\lceil \frac{|S|}{\max_{s_i} \left|N_i^+\right|} \right\rceil$ BD regions. And the conflict nodes is colored with different colors.

Notice in Algorithm 2, each node colors itself with a different color that is not used by any node in the N_i^+; it is straightforward that the algorithm uses at most $\max_{s_i} N_i^+$. Consider two conflicting nodes s_i and s_j, without loss of generality, we assume that $s_i \in N_j^+$. Thus, s_j is colored after s_i has a color that is different from the color of s_i on the basis of the algorithm.

4.3. Examples

We illustrate the results of the aforementioned region partitioning algorithm in several network scenarios. We use NetTopo [29] to depict the different regions of the nodes. The network has the size of 600×400 m^2, with deployed sensor nodes increased from 10 to 90. All nodes have a uniform transmission radius of 150 m, and each node has the same transmission radius and interference radius. We list the number of nodes, average number of neighbors, the number of regions, and the number of colors in each scenario in Table I, where we can find that the region partitioning algorithm is more effective in dense networks. Figure 5 gives an illustration of regions in a WSN with 85 nodes by the distributed region partitioning algorithm.

DOI: 10.1002/cpe

Table I. Results of the distributed region partitioning algorithm.

# of nodes	# of average neighbors	# of regions	# of colors
10	2	6	4
20	4	7	7
30	7	8	12
40	9	8	15
50	11	8	18
60	13	9	27
70	16	10	27
80	18	12	33
90	20	12	36

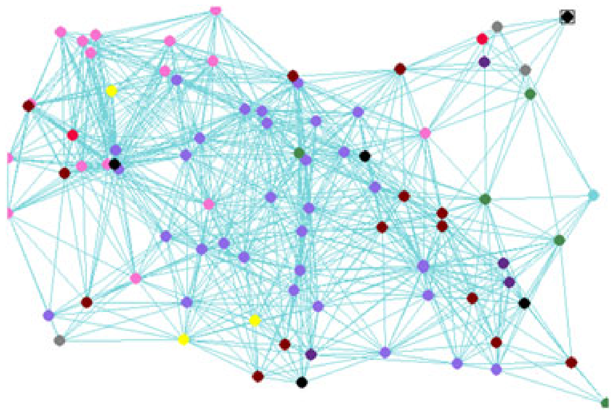

Figure 5. The regions of 85 nodes in the network by the distributed region partitioning algorithm. Each node has the same transmission radius and interference radius, 150 m. There are 10 regions, and each color represents a region. Therefore, the nodes with the same color are in the same region.

5. THE IN-REGION BACKOFF DIFFERENTIATION SCHEME

The proposed BDCR divides the whole network into several BD regions according to the interference relationships among nodes, as described in Section 4. Then, within each region, the BD mechanism is used to improve the throughput of network. Again, the goal is the nodes with more traffic should have more chances for channel access.

5.1. *Proportional fairness backoff scheme*

Suppose a wireless network is divided into R regions, and each region shares a single wireless channel resource. Let J denote the set of the wireless channel resources in the network and C_j be the finite capacity of a wireless resource j. A link l is a nonempty subset of J and L be the set of possible links. Set $A_{jl} = 1$ if $j \in l$, so that the wireless resource j lies on a link l, and set $A_{jl} = 0$ otherwise. Associate a link l with a user, and suppose that if a rate x_l is allocated to a user l, then it has a utility $U_l(x_l)$ to the user. Considering nodes of each regions conflict with each other, there is just one user send packets at the same time. According to [11], the system optimal rates solve the following problem: *SYSTEM*(U, A, C): max $\sum_{l \in L} U_l(x_l)$, subject to $Ax \leqslant C \cap x \geqslant 0$. The problem *SYSTEM*$(U, A, C)$ can be decomposed into the problems *NETWORK*$(A, C; w)$: max $\sum_{l \in L} w_l \log x_l$, and *USER*$_l(U_l; w_l)$: max $U_l(x_l) - w_l$, where w_l could be regarded as an amount to pay per unit time. The unique optimum rate allocation of the network is given by

$$x_l = \frac{w_l}{\sum_{j \in l} \mu_j}, \tag{1}$$

where μ_j is a vector of shadow prices.

Consider the system of differential equations

$$\frac{d}{dt}x_l(t) = \kappa\left(w_l - x_l(t)\sum_{l\in r}\mu_j(t)\right), \tag{2}$$

where

$$\mu_j(t) = p_j\left(\sum_{s:l\in s} x_s(t)\right). \tag{3}$$

We can motivate the relations (2)–(3) as follows: $p_j(y)$ is a price charged by a resource j, per unit flow through the resource j, when the total flow through the resource j is y. For a region R, suppose that the total load $y = \sum_{l\in R} y_l$ on a resource take the form, on a very fine time scale, of a Possion stream of packets at rate y/ε. Time axis is divided into nonoverlapping slots each of length $\tau\varepsilon$. When the packets from a different user l arrive in the resource which is occupied, each of the packets within the slot causes a feedback signal to be sent to the user responsible for that packet. The expected number of feedback signals generated per slot is

$$\sum_{n\in[1,y_l]} ne^{-y\tau}\frac{(y\tau)^n}{n!} = y\tau \sum_{n\in[0,y_l]} e^{-y\tau}\frac{(y\tau)^n}{n!}, \tag{4}$$

and so

$$p_j(y_l) = \sum_{n\geqslant[0,y_l]} e^{-y\tau}\frac{(y\tau)^n}{n!}. \tag{5}$$

We could motivate the equations (5) in the following way: $p_j(y_l)$ is a price offered by the user l, per unit flow through the resource j, when the total flow of user l through resource j is y_l. Considering the backoff mechanism of CSMA, the user l with more flow load should offer a higher price, $p_j(y_l)$, and have a smaller CW cw_l, and the main regulations are as follows:

- If the channel is busy and deferred, the node should backoff. A backoff interval is randomly selected between zero and a minimum CW period $cw_l = \Pi_{i\in R\cap i\neq l}\, p_j(y_i)cw$, where cw is the CW defined by CSMA;
- A collision occurs between two regions; cw_l becomes double every time until $cw_{l\,max}$ is reached, similarly, $cw_{l\,max} = \Pi_{i\in R\cap i\neq l}\, p_j(y_i)cw_{max}$ and cw_{max} defined by CSMA.

5.2. The proof of the proportional fairness

We have obtained a vector of shadow prices in Section 5.1, and we will prove that the rate allocation with the vector of shadow prices is proportionally fair.

Theorem 3
If a vector of rates $x = \left(x_l = \frac{w_l}{p_j(y_l)}, l\in L\right)$ in the network, the vector of rate x is proportionally fair and solves the optimization problem of *NETWORK*$(A, C; w)$.

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ALGORITHM 3. The Complete Centralized-BDCR Algorithm
Input: A communication graph $C = (S, E)$
Output: A vector of the sizes of Contention Windows
1: Construct the conflict graph N_C.
2: Push the vertices of the graph N_C in a stack S. The vertices that have less degree will be pushed first. For the vertices that have the same number of degree, the vertices with smaller ID will be pushed first.
3: **While** S is not empty **do**
4: Pop the top of the stack s_i, mark it with smallest color ID k that is not used by its conflict vertices, and add it into the region R that has no its color.
5: **If** there is no existing region **or** all regions have the same color with s_i **do**
6: Create a new region R and add s_i into R.
7: **For** each region R **do**
8: **For** each vertex s_i in the region **do**
9: Set $cw_i = \Pi_{s_j \in R \cap j \neq i} p(y_j) cw$.

Proof
For any other feasible vector x^* than x, if the aggregate of proportional changes is zero or negative, the vector of rate x is proportionally fair [11]. Without loss of generality, let $x^* = [\cdots, x_{l-1}, x_l^*, x_{l+1} \cdots]$, then the aggregation of proportional changes is as follows:

$$\sum_{l \in L} \frac{x_l^* - x_l}{x_l} = \frac{x_l^* - x_l}{x_l}. \tag{6}$$

- ***Case 1*:** $x_l^* \leqslant x_l$, straightforwardly, Equation (6) is zero or negative.
- ***Case 2*:** $x_l^* > x_l$, according to Equation (1), we can obtain $p_j^*(y_l) < p_j(y_l)$. Equation (6) can be rewritten as

$$\frac{p_j(y_l) - p_j^*(y_l)}{p_j^*(y_l)} = \frac{p_j(y_l) - p_j\left(y_l^*\right)}{p_j\left(y_l^*\right)} = \frac{\sum_{n \in \left[y_l^{star}, y_l\right]} \frac{(y\tau)^n}{n!}}{p_j\left(y_l^*\right)},$$

where $y_l > y_l^*$. By $\lim_{n\to\infty} \frac{(y\tau)}{n!}$, the load of a node, y_l, is a large number, and the result of the aforementioned equation is 0.

□

5.3. *The centralized backoff differentiation under RTS/CTS*

According to the algorithm of centralized BD region under the aforementioned RTS/CTS model and BD scheme, in this section, we can obtain the complete algorithm of centralized-BDCR.

5.4. *The distributed backoff differentiation under RTS/CTS*

Like the centralized-BDCR, we can also combine the distributed regioning algorithm with the design of backoff value to summarize the complete algorithm of distributed-BDCR as follows:

6. PERFORMANCE EVALUATION

6.1. *Simulation*

In this section, we introduce the simulation environment and show the results as well as the analysis for the performance of throughput.

DOI: 10.1002/cpe

Algorithm 4. The Complete Distributed BDCR Algorithm

Input: A communication graph $C = (S, E)$
Output: A vector of the sizes of Contention Windows
1: Each node s_i collects all communication links, say N_i.
2: Each node s_i finds N^+, which is the subset of links in N_i that precedes s_i and let $N_i^- = N_i - N_i^+$.
3: All nodes in N_i^+ is set uncolored by node s_i.
4: **While** some links in N_i^+ are uncolored **do**
5: Node s_i listens messages from other nodes.
6: **if** s_i receives a message $Color(j, k, r)$ **then**
7: Node s_i marks s_j with color ID k and region r if s_j is in N_N^+.
8: s_i colors itself with the minimum color ID, say k, that is not used by any node in N_i^+.
9: **If** the color of s_i is the minimum used color, **do**
10: Mark itself with the region $R = \max_{s_j \in N_i^+}(R_{s_j}) + 1$.
11: **Else** Mark itself with the region $R = \min_{s_j \in N_i^+}(R_{s_j})$.
12: Send the message **Color**(i, k, R) to all nodes in N_i^-.
13: **If** s_i is the sink **do**
14: Color itself with the minimum color ID, say k, mark itself with the region R, and send the message **Color**(i, k, R).
15: **For** each region R **do**
16: **For** each vertex s_i in the region **do**
17: Set $cw_i = \Pi_{s_j \in R \cap j \neq i} p(y_j) cw$.

1) Simulation setup: We use ns-2 simulator [30] to simulate the wireless converge-cast network (WCN); the simulation specifications are shown in Table II. The simulation environment is described as follows. There are 53 nodes randomly placed in a 1000×1000 m^2 area. The maximum communication range between sensors is 250 m [31] (with proper antennas, the coverage of sensor nodes can reach 250 m easily). One sink node is placed in the center of the simulation area. The throughput is measured at the sink node. Each source uses constant bit rate (CBR) traffic source generators to generate user datagram protocol (UDP) packets, as well as a static routing module named NOHA. The reason we use CBR/UDP and static routing is that we want the environment to be as simple as possible, so that we can focus on the MAC protocol performance only, excluding the untractable factors that may affect the overall performance, such as the transmission control protocol's feedback control mechanism and the dynamic behaviors of routing. To analyze the throughput, we run the simulations for nine scenarios, with CSMA-based BDCR protocol and CSMA, respectively. CBR data rates range from 100–900 Kbps so as to show the performances of the tested protocols from low to moderate load and then to congested state.

2) Throughput analysis: Figure 6 shows the throughput results with respect to different CBR source data rates. We can see that at many points, both the centralized BDCR algorithm (C-BDCR)

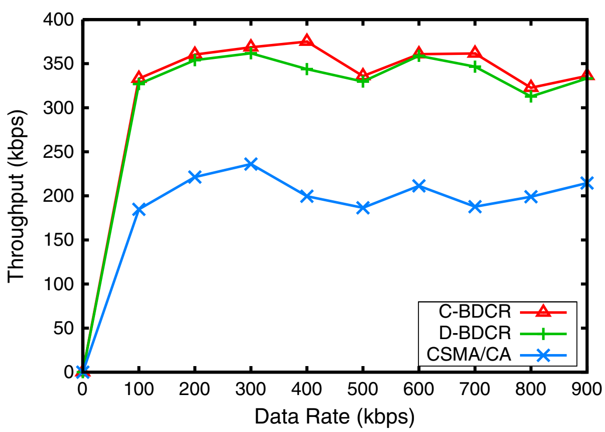
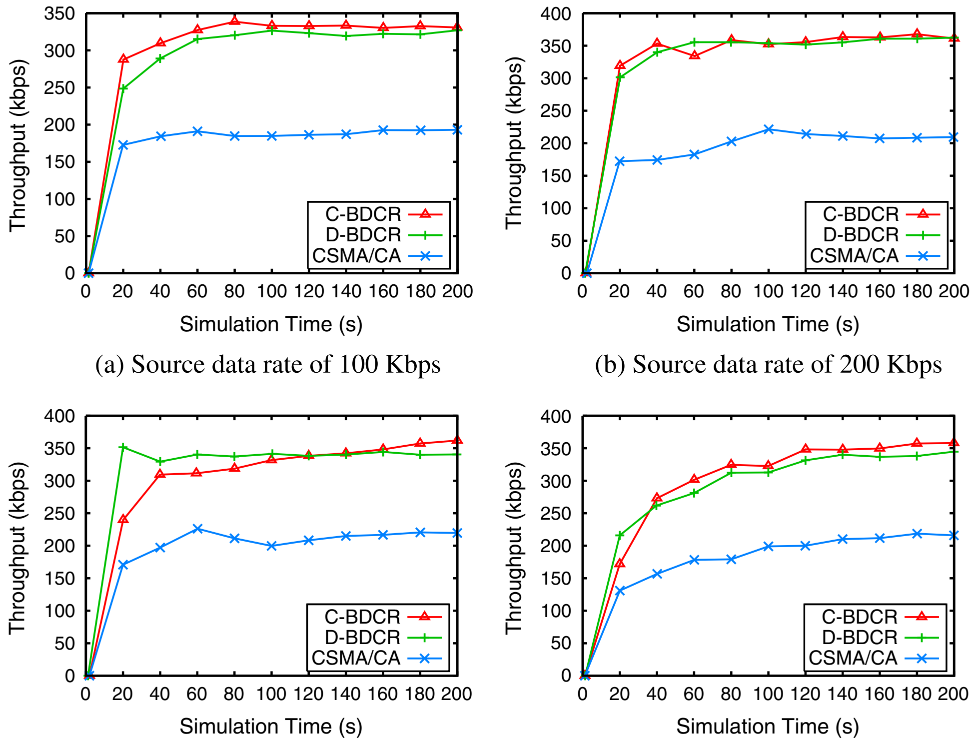


Figure 6. The throughput of BDCR and CSMA with various data rates.

DOI: 10.1002/cpe



(a) Source data rate of 100 Kbps (b) Source data rate of 200 Kbps

(c) Source data rate of 400 Kbps (d) Source data rate of 800 Kbps

Figure 7. The throughput with source data rates of (a) 100, (b) 200, (c) 400, and (d) 800 Kbps.

than the distributed BDCR algorithm (D-BDCR) improves the throughput over CSMA more than 50%, which is very significant. Figure 7(a) and (b) shows that when the network is under light to moderate load, the network throughput of both CSMA and BDCR can quickly reach the stable status, about 180 and 320 Kbps, respectively. However, when the CBR data rate is 800 Kbps, it takes more time to get stable, as shown in Figure 7(d). In most cases, the C-BDCR algorithm works better than the D-BDCR because C-BDCR can obtain more accurate network information, whereas the situations in D-BCDR are not that ideal.

6.2. *Testbed experiments*

We carry on experiments on a real testbed, which consists of 15 nodes made by us as shown in Figure 8. Each node is a Telosb compatible custom mote, named GenOS v1.2, running on MSP430 DSP and CC2420 Radio. GenOS v1.2 mote supports TinyOS 2.x, USB programming, JTAG PORT programming, and single-wire-bus ID chip. It also has a couple of light emitting devices and one digital tube as indicators and uses the single-wire-bus temperature sensor and humidity sensor for sensing. The Li-ion battery supplies power to circuit and corresponding power supply processing circuit as well as USB charging circuit to ensure the off-line running. The main specification is listed in Table III.

To measure the throughput of MAC protocols, we have performed two sets of experiments on CSMA, X-MAC, B-MAC, and our BDCR protocols. The first set of experiments have seven nodes, and the second 15 nodes. Each node runs a slightly modified `RadioSenseToLeds` application, which comes with the standard tinyos 2.x distribution in the `apps` directory. We conduct experiments with source data rates of 10, 20, 50, and 100 pkts per second (pps) on each node for the protocols tested, respectively. The packet size is 30 bytes. The other sets of experiments are the same as the first one except there are 15 nodes, which compose a scenario with higher interferences. We set the power of CC2420 radio to the lowest level (`CC2420_DEF_RFPOWER=1`), so that the

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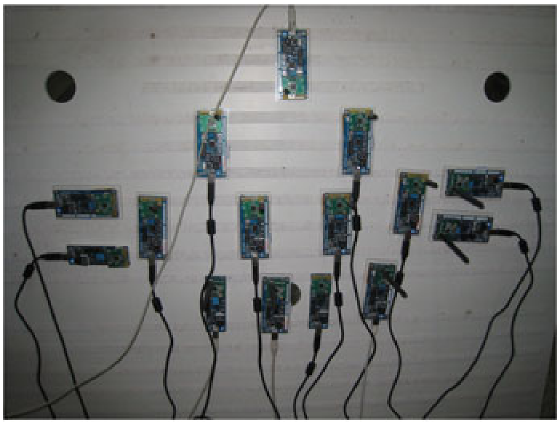


Figure 8. The experimental testbed.

Table II. Simulation parameters.

Parameters	Parameter values
Number of nodes	53
CBR start time (s)	1
CBR stop time (s)	200
CBR frame size (byte)	1500
CBR data rate (kb)	100–900
Bandwidth/Mbps (Mb)	2

CBR, constant bit rate.

Table III. GenOS mote specification.

Specifications	GenOS v1.2
Programming flash	48 kB
RAM	10 kB
Working frequency	8 MHz
ADC	12 bits
DAC	12 bits
Serial communications	UART
Radio module	TI CC2420
Transmit (TX) data rate	250 Kbps
Transmit power	-24 to 0 dbm
Receiving sensitivity	-94 dbm

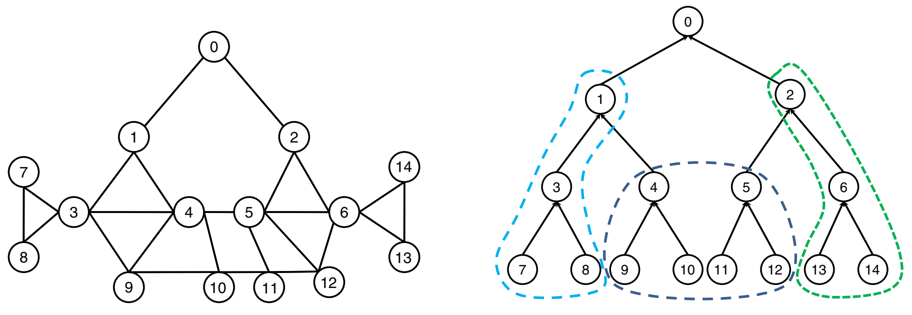
RAM, random-access memory; ADC, analog-to-digital converter; DAC, digital-to-analog converter.

experiments can run multihop scenarios. For B-MAC and X-MAC, we use the wustl's MAC layer address implementations [32] running on tinyos-2.x.

For the first set of experiments, because the testbed is not large enough, we treat the whole testbed as one region to test the pure effect of PFB. For the second set of experiments, by runing the BDCR regioning algorithm, the 15 nodes, whose topology is shown in Figure 9(a) are divided to three regions as shown in Figure 9(b).

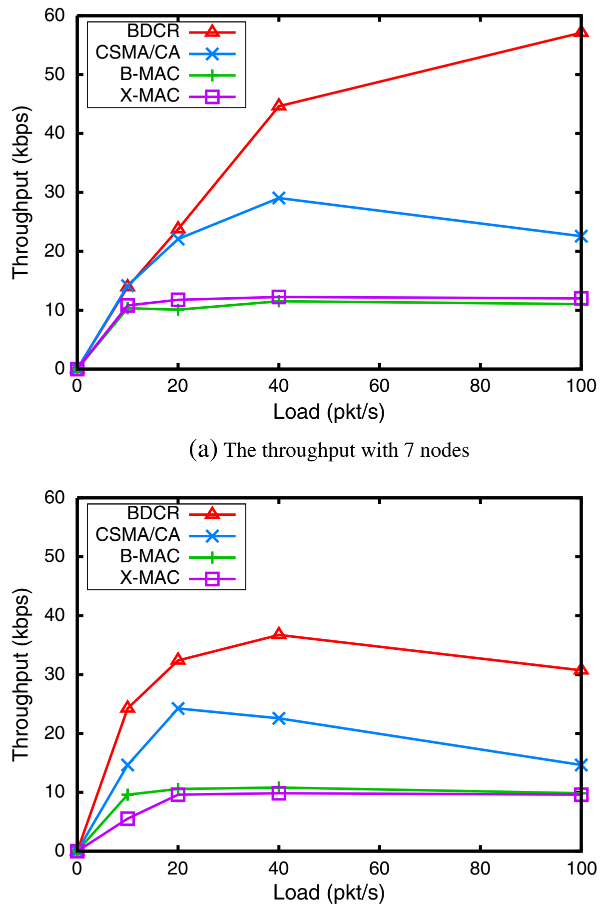
Figure 10(a) shows the results with seven nodes, where the x-axis is the source rate in packet per second (pkt/s) and the y-axis the overall throughput in bit per second (bps). When the source rate is 10 pkt/s, the network is pretty underloaded, and all the four protocols are in the growing segment on the curve. However, we can clearly see that when the packet generation rate increases to 100 pkt/s, which means network is heavily loaded, BDCR does not have any degradation as CSMA does, instead, it still grows and achieves more than 100% gain over the other three protocols. The

DOI: 10.1002/cpe



(a) The topology of the testbed (b) The BD regions

Figure 9. The testbed regioning (15 nodes). (a) The topology of the testbed and (b) the backoff differentiation (BD) regions.



(a) The throughput with 7 nodes

(b) The throughput with 15 nodes

Figure 10. The throughput of testbed with (a) 7 and (b) 15 nodes.

property is perfect for high-throughput WSNs. For the results shown in Figure 10(b), the throughput trends are similar to that of Figure 10(a) except that when the source data rate is greater than 40 pkt/s; BDCR also suffers the degradation but not as significant as CSMA. We conclude that our protocol improves the throughput very well, especially when network is heavily loaded, the case that CSMA works badly.

DOI: 10.1002/cpe

7. CONCLUSION

In this paper, we propose a BDCR scheme based on CSMA MAC protocol for WCN to improve the network throughput under intensive network conditions, in particular aiming at the micro funneling effect. BDCR divides a converge-cast WSN into different regions; then within each region, based on the contention level, it optimizes the channel access for each node by adjusting the backoff window span dynamically. When BDCR conducts the region partitioning, it uses conflict graph techniques and considers the interferences between nodes. Simulation and preliminary testbed results show that BDCR outperforms traditional CSMA and a couple of recent proposed MAC layer protocols in throughput. The superiority becomes much more significant (up to 100%) when the network is highly loaded. Another good property of BDCR is that it has very good scalability feature and is extremely easy to be implemented, in comparison with existing TDMA based solutions.

ACKNOWLEDGEMENTS

This work is partially supported by Natural Science Foundation of China under grant no. 61070181 and Natural Science Foundation of Liaoning Province under grant no.20102021 and Nokia's donation. Lei Shu's research in this paper was supported by Grantin-Aid for Scientific Research (S)(21220002) of the Ministry of Education, Culture, Sports, Science and Technology, Japan.

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DOI: 10.1002/cpe