Intra-Cluster Contention Resolution in Wireless Sensor Networks

Vahid Salmani and Pai H. Chou

Center for Embedded Computer Systems
University of California, Irvine, CA, USA
`{vsalmani,phchou}@uci.edu`

Abstract. Contention resolution plays an important role in designing medium access control protocols. Owing to technical constraints of wireless sensor networks, the task of efficiently resolving contention poses several challenges. In clustered wireless sensor networks, many-to-one communication is the dominant pattern, which is also applicable to the star topology. This paper surveys the state-of-the-art contention-resolution techniques designed for this communication pattern with a discussion of their features and limitations. We closely examine several contention-resolution schemes, including our recently proposed BSTCR algorithm, with performance evaluation in multiple aspects.

Keywords: Contention resolution, clustered WSNs, many-to-one communication, performance evaluation

1 Introduction

In many wireless sensing applications, sensors are grouped around specific points of interest. As a result, a wireless sensor network (WSN) can be deployed as a cluster or set of clusters. In multi-hop networks, the data-collection tree structure is naturally formed as a hierarchy of clusters, and the standard tree-routing protocols can be easily applied to the cluster-tree topology.

In a clustered WSN, nodes in a neighborhood are organized into a cluster, with one node designated as the *cluster head* (CH). A CH is typically a resource-sufficient sensor node that aggregates local traffic and forwards it to the upstream clusters or to the base station. Sensor nodes within the same cluster can communicate directly with their CH; however, they do not communicate among themselves, other than during the initial setup or the CH election phase. Therefore, the dominant communication pattern within a clustered WSN is *many-to-one*.

A medium access control (MAC) protocol coordinates the access to the wireless medium among multiple nodes. The ability to efficiently arbitrate the channel is directly affected by the efficiency of the employed contention-resolution scheme. Designing MAC protocols of WSNs, particularly the contention-resolution part thereof, is a challenging task due to the several technical limitations exposed to these networks. We review some of those challenges in Section 2.

In Section 3, we survey the state-of-the-art contention-resolution schemes designed or suited for (but not necessarily limited to) clustered WSNs and the many-to-one communication pattern. Our focus is on *intra-cluster* contention resolution, and thus schemes such as BCCR [1] that deal with multiple contention regions and work across multiple hops are outside the scope of this work. To the best of our knowledge, this is the first survey and critical review specifically on contention resolution in WSNs.

To study the performance of some of the surveyed methods, we developed a simulator whose details are presented in Section 4. We perform a stand-alone simulation-based comparison of some recently proposed contention-resolution approaches in Section 4.1. In Section 4.2, we present a comprehensive performance evaluation of two recently proposed receiver-initiated contention resolution schemes, namely BSTCR [2] and Strawman [3] within a receiver-initiated MAC protocol. Finally, Section 5 concludes this paper.

2 WSN Constraints

Contention resolution has been a fundamental research topic for decades. However, many of the schemes designed for wired or even wireless networks are simply not applicable to WSNs due to the peculiarities of these networks. In this section, we review some of the challenges mandated by limitations and characteristics of WSNs.

a) **Limited battery life:** The scarcest resource of a wireless sensor node is its battery power. As a result, a node often cannot afford to continuously monitor the medium due to energy constraints. To address this problem, duty cycling and back-off techniques have been proposed, which may increase the risk of collisions and wasted idle slots, respectively.
b) **Transceiver delays:** In low-power transceivers, a signal cannot be detected if it has not been present for a minimum duration. For example, in case of the CC2420 transceiver, the signal is not detected if transmission is started within the last 128 μs. Moreover, a node is not able to sense the channel during the RX/TX switching phase.
c) **Imperfect collision detection:** A wireless transmitter is not able to detect collision if it cannot transmit and listen to the channel at the same time, which is often the case with most transceivers for WSNs. Receiver-side collision detection (RCD) is possible but can be prone to false positives in the presence of external interference. Moreover, the accuracy of some RCD techniques decreases as the number of colliding nodes increases [4]. Also, it is often not possible to explicitly identify the transmitters involved in the collision.
d) **Control packet overhead:** In WSNs, the packet size is typically small (less than a few hundred bytes) and even the smallest control packets can constitute large overhead. For instance, reference [5] reports that an RTS-CTS-DATA-ACK handshake series in transmitting a packet can amount to

40% overhead on their platform. Therefore, a contention-resolution scheme should minimize the number of control packets.

e) **Dynamic nature:** The number of nodes in a WSN or the number of contenders for the medium may not be known or fixed. Nodes can join or leave for several reasons. In event-driven networks, the number of contenders triggered on each event may vary. With the exception of underwater acoustic sensor networks [6], obtaining the number of contenders often requires explicitly querying the nodes in the WSN.

3 Contention Resolution Survey

Contention resolution is an integral component of contention-based and hybrid MAC protocols. Contention-based MAC protocols can be classified into sender-initiated and receiver-initiated. In the *sender-initiated* class, the most common contention-resolution technique is back-off-based collision avoidance. In *receiver-initiated* protocols, the receiver initiates a data transfer by transmitting a probe, also known as *ready-to-receive* packet.

3.1 Sender-Initiated

Optimal CSMA CSMA/p^* [7] is non-persistent CSMA and uses the optimal non-uniform distribution p^* in determining the channel access probability. It minimizes the collision probability if the number of contenders is known but delivers suboptimal performance otherwise.

To relax the above constraint, the same authors use a truncated geometric distribution that approximates p^* with a fixed-size contention window in Sift [8]. Designed for event-driven networks, Sift takes advantage of the *spatially correlated contention* property of sensor networks and yields low latency for a subset of reports triggered by the same event while suppressing the rest.

Although Sift achieves high success probability for channel access and reduced collision probability, it assumes a minimum number of contenders are present at all times. Moreover, it might not perform well either in case of highly random data arrivals to a node or with those applications requiring timely packet delivery by the contenders.

Backoff Preamble Sequential (BPS) A limitation of low-power transceivers is a node's inability to detect an ongoing transmission if the signal has not been present for the minimum duration. To cope with the above problem, BP-MAC [9] uses a back-off preamble (BP) of a random length (and depending on a retry counter), which functions as both medium reservation and busy signals. Having sent the BP, the node senses the medium and starts transmitting data if it finds the channel to be idle. Otherwise, the node backs off before it senses the channel again.

This approach does not guarantee a successful resolution, as two or more nodes may choose the same BP duration and start data transmission simultaneously. To alleviate this problem, BPS-MAC [10] uses a sequence of short consecutive BPs to reduce the contention step by step. To improve the probability of success, nodes use a truncated geometric distribution for determining the BP length and start data transmission only after a predefined number of BPs have been successfully transmitted.

A problem with this approach is that it requires manually tuning several parameters for the best performance, and finding the best configuration may be non-trivial. Moreover, contention resolution is not guaranteed to be successful due to the same BP length chosen by more than one node, although the latter issue could be resolved using ACK messages.

Fast Collision Resolution (FCR) The main shortcoming of back-off-based collision avoidance approaches comes from collisions and wasted idle slots due to back-offs. When the number of contenders increases, many of them back off with small contention windows. Therefore, with high probability, many of the retransmission attempts will collide again in the future. Designed for wireless LANs, FCR [11] is aimed at solving the above issues by redistributing the back-off timers for all contenders to speed-up the collision resolution.

With FCR, all active nodes monitor the medium. When a deferring node detects a predefined number of consecutive idle slots, it reduces the back-off timer exponentially. On the other hand, when the start of a new busy period is detected, the node increases the contention window size and picks a new random back-off time to give the backlogged packets more time to finish.

A drawback of FCR is that it requires active nodes to constantly perform carrier sensing as long as they have data to send. Since monitoring the channel at all times is impractical in WSNs due to high energy consumption, the combination of FCR with coordinated sleeping has been proposed [12]. This adaptation comes at the cost of performance. While the algorithm performs better than IEEE 802.11 under low duty cycles, its performance under high contention has not been explored.

3.2 Receiver-Initiated

Synchronized, Shared Contention Window (SSCW) Designed for periodic data collection applications, SSCW [13] uses a fixed-size contention window based on the number of nodes. To prevent a single node from colliding more than once in the same window, SSCW uses non-overlapping contention windows. Packets collided in a given window are rescheduled at random times in the next window starting immediately after the current window.

A data-collection cycle starts with a synchronization beacon from the CH. Having successfully transmitted its packet, each node returns to RF silence and waits for the next beacon. In case of a failure, inferred by the absence of an ACK message, the node attempts a retransmission in the next window, and this process repeats until all nodes have delivered their data packet.

Authors of [14] proposed successively decreasing contention windows to improve the efficiency of SSCW based on the observation that the number of contenders will be decreasing in subsequent windows. For this purpose, the remaining nodes recalculate the windows size based on the number of current (i.e., last collided) contenders.

The main limitation of SSCW is that the number of contenders must be known in advance. Therefore, it cannot be used as a general contention-resolution technique. Moreover, it assumes that nodes always have data to transmit and that all nodes contend for the medium. Finally, the contender must keep track of the number of ACK packets from the CH, which requires a node to be listening at all times.

Flip-MAC Designed for dense networks, Flip-MAC [15] resolves contention in two steps. First, it employs a contention-reduction technique based on a series of probe-acknowledgment cycles. In each cycle, contenders set their ID to one of two possible addresses randomly, and those that guessed correctly send simultaneous acknowledgment while the rest are out of competition. As long as the CH detects a carrier, it keeps sending the probe, which results in a logarithmic complexity.

The second step starts when a probe goes unacknowledged, at which point the CH broadcasts a confirmation message indicating that the contention level has dropped to a manageable level. Subsequently, the few remaining contenders use a common resolution technique such as back-off-based CSMA to select the winner.

Flip-MAC implements the probes as hardware-generated acknowledgments on the CC2420 transceiver to improve the efficiency. However, this feature may not be supported by all transceivers and thus have to be implemented as separate transmissions. Another consideration with Flip-MAC is that finding the best time to stop the CSMA/back-off scheme to start a new round of contention reduction may not be trivial. The receiver may have to wait for an interval of RF silence of at least as long as the maximum contention window to make sure that no node is backing off, which wastes the bandwidth.

Strawman Designed for receiver-initiated radio duty-cycling protocols, Strawman [16] handles contention based on the analogy of drawing straws. The process starts with a probe message from the CH. The simultaneous senders then draw a random number for the length of the request signal, and the channel access is granted to the sender of the longest straw. The CH announces the winner via a decision message containing the length of the longest request signal.

A downside of Strawman is that it fails if two or more contenders share the longest request. Its enhanced version, called E-Strawman [3], solves this issue by resolving collisions in steps while keeping the average lengths of straws as short as possible. By announcing the length of the longest received signal, the receiver authorizes only the colliding winners of the current round to participate in the next round until a successful transmission occurs. The length of straw is determined randomly using a truncated decreasing geometric distribution. In a recent paper [17], Strawman uses multiple channels to further reduce contention.

For the best performance, this approach needs to be provided with the number of contenders that will be used in the first round to calculate the maximum straw length. From the second round on, the estimated average of colliding winners is used to recalculate the maximum request length, because the number of actual winners is unknown. Another consideration is that the maximum straw length cannot scale with the number of contenders as the payload length is limited. Moreover, the maximum signal length may not be estimated with 100% accuracy [17].

Tree-Splitting The tree-splitting [18] technique is a recursive operation that randomly divides a group of colliding packets into two subgroups, each of which is subject to the same procedure as the original group. Nodes that are not involved in the collision wait until the collision is resolved. Therefore, no newly arrived packet is transmitted while the resolution of a collision is in progress. With this approach, the number of contenders or colliding nodes does not have to be known.

A combination of tree-splitting and binary exponential back-off (BEB) schemes is used in [19] to speed up the resolution in case of a small number of contenders and to maintain compatibility with random-based MAC protocols in (low-data-rate) heterogeneous networks. Having divided the collision domain and in case of a collision, inferred by the absence of an ACK, the contenders switch to the back-off-based resolution scheme. Once the first packet is successfully delivered, the CH resumes the splitting operation for the current domain. Although this approach shortens the resolution for low-data-rate networks, it may lead to a prolonged resolution under higher levels of contention.

The Binary Search Tree Collision Resolution (BSTCR) [1] scheme [2] uses a variant of tree-splitting where the collision domain is represented as a "range" of node IDs. Instead of randomly dividing the contenders, the collision domain is split exactly in half, which results in a deterministic contention resolution. Moreover, it is possible for new contenders to access the medium during the resolution process. To the best of our knowledge, BSTCR is the only non-negotiation-based technique, i.e., it does not incorporate any random component. For that reason, it is the only deterministic method in terms of the required steps for resolving contention.

3.3 Summary

Contention-resolution techniques can be classified into received-initiated and sender-initiated. Receiver-initiated schemes are triggered by probe messages from the CH and usually rely on collision detection at the CH. On the other hand, sender-initiated methods are usually back-off based. Either class may leverage

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[1] Although we originally used the acronym BTCR, BSTCR is more accurate because we treat the collision domain as an *ordered* list of *unique* node IDs.

Table 1: Summary of the surveyed contention resolution schemes

	CSMA/p^*	Sift	BP-MAC	BPS-MAC	FCR	SSCW	Adaptive SSCW	Flip-MAC	Strawman	E-Strawman	Tree-Split+BEB	BSTCR
Reference number	[7]	[8]	[9]	[10]	[12]	[13]	[14]	[15]	[16]	[3]	[19]	[2]
Receiver initiated						✔	✔	✔	✔	✔	✔	✔
Knowledge of the number of contenders	✔					✔	✔					
Carrier sensing on contenders	✔	✔	✔	✔	✔			✔			✔	
Back-off based	✔	✔	✔	✔	✔	✔	✔	✔			✔	
Receiver-side collision detection based								✔	✔	✔	✔	✔
Preamble based			✔	✔					✔	✔		
ACK messages required		✔				✔	✔				✔	

preambles of random length in combination with back-off or RCD methods. The most common component of contention resolution is carrier sensing, which is used in all surveyed methods except SSCW. In receiver-side collision resolution, the CH performs carrier sensing to accomplish the RCD operation. ACK messages are mandatory in some cases, but can help the resolution operation in general. Table 1 compares the surveyed approaches from different aspects.

4 Performance Evaluation

Since conducting real experiments is costly and time-consuming, especially with a large number of nodes, we essentially use simulations for performance evaluation. We have developed a simulator [2] in Java, which runs at symbol-period-level granularity to conduct our evaluations in a more controlled environment than existing simulators can provide. The standard models of the existing network simulators such as ns-2 or OPNET assume that a transceiver does not need any time to sense the channel or to switch between TX and RX modes [10]. The widely used TOSSIM simulator fixes this issue, but it simulates only nodes running TinyOS [20].

We have simulated the Telos platform, which incorporates a TI CC2420 radio transceiver. CC2420 is popular and is used by the majority of the surveyed techniques in Section 3. Moreover, the timings of CC2420 has been widely studied and well understood. We have taken the timer values such as RX/TX switching, CCA sampling, radio on/off transition, etc., from the data sheet [3]. Other pro-

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[2] Source code is available at
`http://newport.eecs.uci.edu/~vsalmani/download/mac_sim.tar.gz`

[3] CC2420 data sheet – 2.4 GHz IEEE 802.15. 4/ZigBee-ready RF Transceiver:
`http://www.ti.com/lit/ds/symlink/cc2420.pdf`

cessing times such as RX/TX buffering times are also taken into account using the measurements presented in [21]. The physical layer is defined according to the IEEE 802.15.4 standard. In addition, we have implemented the automatic acknowledgment feature of the CC2420 radio transceiver.

The rest of this section is dedicated to evaluation of some of the surveyed methods, which will be fulfilled in two parts. First, we perform a stand-alone and abstract comparison to see how the algorithms perform regardless of the underlying MAC protocol. Next, we assess the performance of the compared algorithms in the context of a light-weight MAC protocol in a more realistic scenario.

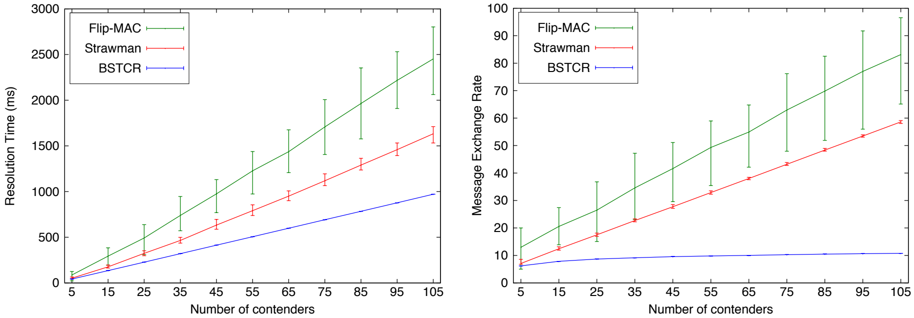
4.1 Stand-alone Evaluation

We select the evaluation candidates among the surveyed approaches in Section 3.2 because the majority of the recently proposed contention-resolution schemes have been receiver-initiated. Moreover, the presented results in this section will be complementary to our previous experiments in [2]. We choose Flip-MAC [15], (Enhanced) Strawman [3], and BSTCR [2] for further analysis. Because they are general-purpose and fairly robust approaches, they can be used as the contention-based component of the majority of MAC protocols and wireless-sensing applications. Since the selected algorithms are based on receiver-side collision detection, we assume that the CH can successfully detect all collisions. Also, we assume perfect straw length estimation on the CH as the best case for Strawman.

In this section, we compare the three approaches as independent and stand-alone modules. In this scenario, each contender successfully transmits an "ADD" message to the CH and then quits the competition. In case of Flip-MAC and Strawman, new rounds are started immediately after completion of the current round until all contenders successfully transmit their message. We simulated a cluster composed of 5 to 105 sensor nodes and a CH. The experiment was repeated 100 times, and the results were averaged out.

Fig. 1a shows the *total resolution time*, i.e., the time that the last contender takes to deliver its "ADD" packet. The completion time grows linearly with the number of contenders for all three algorithms. However, BSTCR outperforms the others, because unlike Strawman, it reduces the contention in half, and unlike Flip-MAC, it keeps splitting until one contender is left. The reason for Flip-MAC's longer time is that in each round, it has to start splitting for *all* remaining contenders, whereas BSTCR does not split the same collision domain more than once but just backtracks to the already reduced contention for subsequent splitting. Moreover, Flip-MAC has to wait for an interval of RF silence before starting the next round (see Section 3.2).

We define *control message exchange rate* as the total number of exchanged control packets divided by the total number of contenders. In other words, this parameter shows how many messages are required on average for each contender prior to being granted access to the medium. As depicted in Fig. 1b, BSTCR is far superior to others, because the number of exchanged messages it requires is



(a) Total resolution time

(b) Control message exchange rate

Fig. 1: Total resolution time (a) and control message exchange rate (b) as functions of number of contenders

logarithmically proportional to the number of contenders, whereas in Flip-MAC and Strawman, the message overhead scales linearly. As a result, BSTCR would impose much less overhead on the MAC protocol.

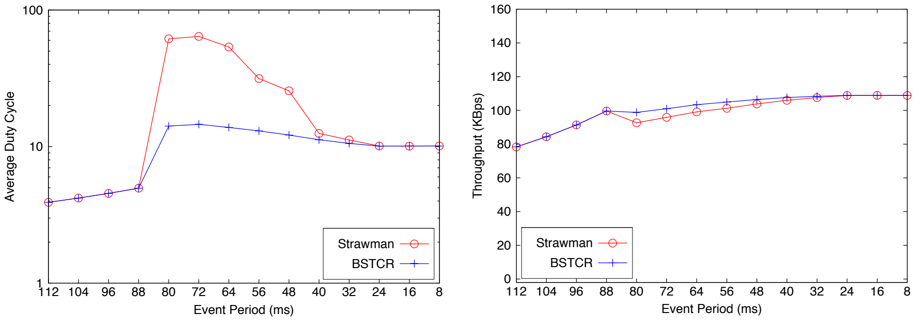
Scalability has been a challenge in MAC design. Contention resolution as a key component of any hybrid MAC can greatly influence the overall scalability of the protocol. It can be inferred from Fig. 1 that BSTCR is better-suited for handling larger scales and in particular can lead to better scalability in terms of the overhead imposed by control packets.

It is worth mentioning that completion times of Flip-MAC and Strawman fluctuate across different runs, because they incorporate a random component. In contrast, BSTCR is deterministic and always demonstrates the same performance. The determinism of BSTCR makes it more suitable for applications with real-time constraints.

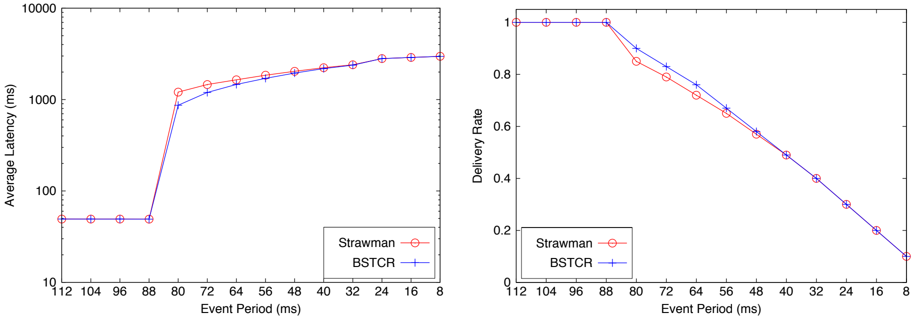
4.2 Holistic Evaluation

Based on the results from the previous section, we decided to continue the evaluations with BSTCR and Strawman only. In [17], Strawman and Sift were compared as the contention-based component of the RI-MAC [22] protocol, and the results indicated the superiority of Strawman. In this section, we evaluate BSTCR and Strawman as the contention-based component of a lightweight hybrid MAC protocol.

A hybrid MAC protocol is usually composed of schedule-based and contention-based parts. Contention resolution is used as the contention-based component. We choose Bin-MAC [2] to serve as the MAC protocol. Bin-MAC is a receiver-initiated protocol and belongs to the scheduled-contention category. It works in a round-robin style and supports duty cycling, which makes it a good match for Strawman. BSTCR is the default contention resolution scheme for Bin-MAC. Bin-MAC represents each slot as a range of node IDs. In case of a collision,



(a) Average duty cycle (b) Throughput



(c) Average latency (d) Data delivery rate

Fig. 2: Average duty cycle (a), throughput (b), average latency (c), and data delivery rate (d) as functions of number of contenders

the contention-resolution method is triggered and the colliding nodes can acquire their own time slot. A distinguishing feature of Bin-MAC is that it retains the results of the already resolved contention across rounds and deals with only newly occurring contention.

In our implementation of Strawman on Bin-MAC, when a collision occurs in a time slot, we repeatedly run Strawman round by round and keep track of the winners. Once all collisions are resolved, the winners list is sorted and the time slot is split so that each contender acquires its own time slot.

In our simulations, we model a cluster composed of 20 sensor nodes and a CH. Simulation time is 2x10^7 symbol periods. We vary the event period from 112 ms to 8 ms to evaluate the performance under very low to very high contention. Each event is assumed to require 10 successful transmissions (1100 bytes) to be reported completely. We assume the data buffer on each sensor node to be 2 KB.

In WSNs, the *duty cycle* and communication-related energy consumption are directly related. Contention resolution has an impact on duty cycling, because the contenders cannot keep their usual sleep/wake-up schedule while they are involved in the resolution process. Duty cycle is defined as the percentage of time the radio is on, including the time the radio is sending, receiving, or listening. These three modes of operation consume roughly the same energy [21].

Fig. 2a shows the average duty cycle. Under very low and very high load, the two algorithms have similar performance due to the lack of contention. Note that under high loads, all nodes acquire their own slot and Bin-MAC performs like a fully reservation-based round-robin protocol. Under medium loads, however, BSTCR shows better performance, because it resolves the contention faster and thus the nodes can switch back to duty cycling earlier compared to Strawman.

Fig. 2b shows the average throughput. Under low loads, both algorithms utilize the bandwidth as much as possible. In overloaded conditions, both algorithms reach the maximum throughput as a pure round robin can. Under medium loads, both algorithms experience some throughput degradation, though it is almost negligible in case of BSTCR.

The average latency is depicted in Fig. 2c. As the load reaches a certain threshold and collisions start to happen at event period 80 ms, the contention resolution-algorithms are triggered and we see a sudden increase in average latency in reporting events. BSTCR shows a slightly better latency, but both algorithms gradually converge in performance.

Finally, we define *delivery ratio* as the number of successfully reported messages to the total number of generated messages. Fig. 2d shows the observed delivery ratio. BSTCR's performance degrades with an almost fixed slope, meaning that it is able to deliver nearly as many messages as a pure round robin can. However, Strawman shows slightly worse performance under medium loads. We refer the reader to [2] for a comparison of Bin-MAC, which utilizes BSTCR as the contention mechanism, with three other protocols.

5 Conclusions

Contention resolution has been a challenge to medium access control protocol designers. We provide reasons why MAC design is even more challenging in WSNs. We present a survey of the state-of-the-art techniques for resolving many-to-one contention in clustered WSNs. We review the categorization, essential components, use-cases, and pros and cons of the surveyed methods.

Using extensive simulations, some of the recently proposed approaches of contention resolution is evaluated. To assess the algorithms more comprehensively, we break the evaluation process into the stand-alone and holistic (i.e., part of a MAC) steps. More specifically, our evaluation is focused on Strawman and BSTCR techniques. The results show the superiority of BSTCR, as it resolves contention faster while requiring less control-packet exchange. It also leads to better scalability and determinism.

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