# Z-MAC: a Hybrid MAC for Wireless Sensor Networks *

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## ABSTRACT

Z-MAC is a hybrid MAC protocol for wireless sensor networks. It combines the strengths of TDMA and CSMA while offsetting their weaknesses. Nodes are assigned time slots using a distributed implementation of RAND. Unlike TDMA where a node is allowed to transmit only during its own assigned slots, a node can transmit in both its own time slots and slots assigned to other nodes. Owners of the current time slot always have priority in accessing the channel over non-owners. Therefore, under low contention where not all owners have data to send, non-owners can "steal" time slots from owners. This has the effect of switching between CSMA and TDMA depending on contention. Z-MAC is robust to topology changes and clock synchronization errors; in the worst case its performance falls back to that of CSMA. We implemented Z-MAC in TinyOS and evaluated its channel utilization, energy, latency and fairness over single-hop, two-hop and multi-hop sensor network topologies constructed using Mica2. The result shows that Z-MAC has remarkably better data throughput than existing sensor MAC protocols while consuming comparable energy (over three times better throughput under high contention).

## Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless communication

## General Terms

Experimentation, Performance, Algorithms

## Keywords

Wireless Sensor Networks, Medium Access Control, Network Performance

*A full version of this paper can be found at http://www.csc.ncsu.edu/faculty/rhee/export/zmac



## 1. INTRODUCTION

In wireless sensor networks, CSMA, such as SMAC [4] and BMAC [1], is most commonly used due to its simplicity, flexibility and robustness. It does not require clock synchronization or topology information, and dynamic node join/leave is handled gracefully without any extra cost. However these features come at the cost of trial and error – a trial may cost access *collision* where more than two "conflicting" nodes transmit at the same time causing signal fidelity degradation at destinations. Collision is particularly more costly for sensor networks because it wastes energy as neighboring nodes may be engaged in idle listening for unsuccessful transmission. Because of collision, CSMA severely degrades its data throughput and wastes energy under high contention. Hidden terminals are the primary cause of collision. Although RTS/CTS can help solve the hidden terminal problem, the scheme still incurs high overhead in sensor networks because data packets are typically very small. A recent benchmark test [1] indicates that RTS/CTS reduces the effective throughput of B-MAC, the default MAC of Mica2, by over 75%.

TDMA solves the hidden terminal problem by scheduling transmission times of conflicting nodes at different times. However, developing an efficient schedule with high degree of concurrency is very hard (i.e., NP-hard [2]). Furthermore, it does not adapt to time varying dynamics of the networks such as node failures, topology changes, and time synchronization errors. Finally, during low contention, TDMA gives much lower channel utilization and higher delays than CSMA since a node can transmit only during its scheduled time slots.

## 2. Z-MAC

We present a new hybrid MAC scheme - *Z-MAC*, for sensor networks. Z-MAC behaves like CSMA under low contention and like TDMA under high contention. Unlike TDMA, it is robust to dynamic topology changes and time synchronization failures commonly appearing in sensor networks. It also handles hidden terminals with very little overhead, unlike CSMA.

We use *DRAND*, an efficient scalable channel scheduling algorithm [3]. DRAND is the first distributed implementation of RAND [2], a well-known centralized channel reuse scheduling algorithm, and thus achieves the same channel efficiency as RAND but only with $O(\delta)$ average message and running time complexities. $\delta$ is the number of two-hop neighbors (so its performance depends only on the local properties of the network). After the slot assignment, each

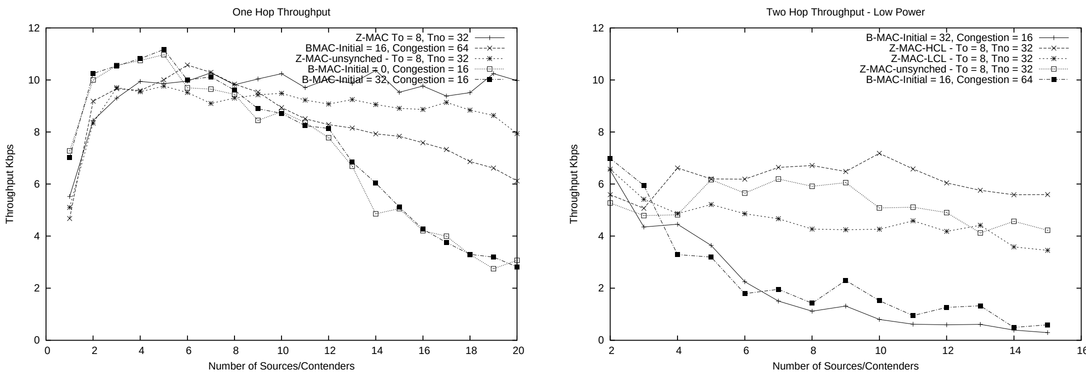


**Figure 1: The data throughput in one-hop (left) and two-hop (right) environment with different congestion window sizes and no duty cycle.**

node reuses its assigned slot periodically in every predetermined period, called *time frame*. We call a node assigned to a time slot an *owner* of that slot and the others the *non-owners* of that slot. There can be more than one owner per slot because DRAND allows any two nodes separated by more than two hops to own the same time slot.

In Z-MAC, a node may transmit at any time slot. As in CSMA, before a node transmits in a slot, it always performs carrier-sensing and transmits a packet when the channel is clear. However, an owner of that slot has priority over its non-owners in accessing the channel. The priority is implemented by adjusting the initial backoff period; higher priority nodes have shorter backoff periods. The goal is that during the slots where owners have data to transmit, Z-MAC reduces the chance of collision since owners are given earlier chances to transmit and their slots are scheduled a priori to avoid collision, but when a slot is not in use by its owners, non-owners can steal the slot. This priority scheme has an effect of implicitly switching between CSMA and TDMA depending on the level of contention.

In Z-MAC, a node can also explicitly switch between two modes of operation depending on the current level of network contention. Under low contention, non-owners are allowed to compete in any slot with low priority. We call this mode the *low contention level* (LCL). This contention resolution may still cause hidden terminals (and collisions) over two hops under high contention because carrier-sensing does not work beyond one hop. When a node starts experiencing more data contention (detected by repeated losses of ACKs or frequent congestion backoffs), it switches its mode to the *high contention level* (HCL). Under HCL, a node does not compete in a slot owned by its two-hop neighbors and thus, non-owners do not act as hidden terminals to the owners.

Z-MAC needs only local clock synchronization among *senders* in two-hop neighborhoods. We devise a simple local synchronization scheme where each sending node adjusts the synchronization frequency based on its current data rate and resource budget (receivers do not send synchronization messages). Our analysis shows that even in the case when clocks are completely unsynchronized, Z-MAC has a comparable performance to CSMA, if not better. As senders transmit more data, time synchronization becomes more accurate and then the performance of Z-MAC significantly improves, reaching that of TDMA under high contention (i.e., high channel utilization, low overhead, quality of service), and that of CSMA under low contention (i.e., high channel utilization, low delay).

# 3. PERFORMANCE RESULTS

Z-MAC has been implemented in TinyOS. Experiments were conducted on Mica2 motes. Single-hop and two-hop environments were created by varying the transmission power of $n$ motes sending as fast as they can to a single source. We present the results comparing the channel utilization of Z-MAC with B-MAC (Figure 1). The energy and latency of Z-MAC are comparable to those of BMAC whose results can be found in the full poster. Figure 1 shows that Z-MAC achieves more than 3 times the throughput of B-MAC under high contention, especially in the two-hop case, where the hidden terminal problem manifests itself. This result includes the overhead of clock synchronization. It also shows the performance of Z-MAC when the clocks are not synchronized (denoted Z-MAC-unsynched) whose throughput is in fact better than that of B-MAC.

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