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# Queen-MAC: A quorum-based energy-efficient medium access control protocol for wireless sensor networks

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A B S T R A C T

Major problems in the Medium Access Control (MAC) of Wireless Sensor Networks (WSNs) are: sleep/wake-up scheduling and its overhead, idle listening, collision, and the energy used for retransmission of collided packets. This paper focuses on these problems and proposes an adaptive quorum-based MAC protocol, Queen-MAC. This protocol independently and adaptively schedules nodes wake-up times, decreases idle listening and collisions, increases network throughput, and extends network lifetime. Queen-MAC is highly suitable for data collection applications. A new quorum system, dygrid is proposed that can provide a low duty cycle, $O(1/\sqrt{n})$, for adjusting wake-up times of sensor nodes. Theoretical analysis demonstrates the feasibility of dygrid and its superiority over two commonly used quorum systems (i.e., grid and e-torus). A lightweight channel assignment method is also proposed to reduce collision and make concurrent transmissions possible. Simulation results indicate that Queen-MAC prolongs the network lifetime while increasing the average delivery ratio and keeping the transmission latency low.



## 1. Introduction

Wireless Sensor Networks (WSNs) [1] have recently received much attention worldwide from military, industry, medical and health, urban traffic monitoring, and academia. WSNs are composed of many sensor nodes, each capable of gathering, processing, storing, and transferring environmental information. These nodes are usually organized in an ad hoc fashion. They operate in a distributed manner and coordinate with each other to accomplish a common duty.

The protocols designed for WSNs greatly depend on the applications for which the network has been established. Nonetheless, in many applications, one of the more serious challenges is how to increase the network lifetime now limited by the energy restriction of sensor nodes. Several factors are involved in the energy loss of nodes: collisions, retransmissions, idle listening, overhearing, and protocol overhead. The radio of a sensor node uses more power. The node usually turns its radio off, goes to sleep mode to save energy, and wakes up according to its predetermined schedule to transmit data. This method is called a duty cycling or a sleep scheduling [2], which is widely proposed for use in the Medium Access Control (MAC) protocol of multi-hop networks [3–8]. Different modes of a sensor node are shown in Fig. 1.

If designed properly, a MAC protocol can result in low power consumption and consequently increase the network lifetime. Most MAC protocols proposed for WSNs are based on the use of a single channel [8–17]. Such MAC protocols, especially in high-density deployments, increase collisions as well as end-to-end delay, and ultimately reduce the network lifetime. Several multi-channel MAC protocols [18–30] have been proposed recently with various objectives, e.g., handling burst traffic, fairness, reliability in data collection, evading external interference, improving throughput, and end-to-end delay. However,

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energy saving is still an important issue. Existing energy saving mechanisms can be categorized into three types: synchronous, asynchronous, and on-demand wake-up [2].

Synchronous MAC protocols [18–20,22–27] normally maintain a schedule that specifies when a node should be awake to check the medium. These protocols cannot adapt to an individual's traffic well. In asynchronous MAC protocols [21,28,29] nodes independently schedule their wake-up times to periodically check the channel. When a node has data to send, it transmits a preamble that is long enough to be detected by the destination node. After preamble detection, the destination node stays awake to get the data following the preamble. These asynchronous protocols avoid the synchronization overhead. However, the long preamble results in longer latency and more energy consumption [31]. For on-demand wake-up protocols [30], nodes are equipped with a secondary low power radio to wake up its main radio to be ready for data exchange. Using multiple radio transceivers has some shortcomings. Radio transceivers consume energy, even while asleep, so increase the energy consumption of the nodes. In addition, a multiple radio transceivers system needs higher performance communication mechanisms and processor capabilities to receive and process data (or signals) from multiple channels.

Quorum systems recently have been utilized to design protocols for wireless networks [7,8,32–36]. There are several kinds of quorums: grid-based [37], torus [38], extended torus (e-torus) [32], and so on [35]. Some of them, such as grid and torus, have fixed duty cycles that makes them inappropriate for use in a network with different traffic conditions. The others such as e-torus, which has an adaptive duty cycle, provide a high minimum duty cycle that leads to more energy consumption if used in a network with a low traffic load.

This paper proposes a new quorum system, "dygrid". It surpasses existing quorums such as grid-based quorums [6,8,39], and e-torus [32], in terms of duty cycle, the number of rendezvous points, and network sensibility as discussed in Section 3.2. Utilizing adaptive dygrid, our proposed MAC protocol named "Queen-MAC" can save more energy while keeping the transmission latency low. For more energy saving, we also propose a lightweight channel assignment method to reduce collision and increase network throughput. Moreover, adaptive matching of wake-up intervals in Queen-MAC makes it flexible in different traffic conditions. Both theoretical analysis and simulation results are given to evaluate the performance of Queen-MAC in comparison with existing quorum-based [8] and multi-channel [28] MAC protocols. Theoretical analysis results demonstrate that the proposed protocol is more energy efficient while providing better network latency. Simulation results using OPNET Modeler 14.0 [40] verify that Queen-MAC increases the network lifetime and reduces network latency. The results also show that the performance of Queen-MAC is more significant in higher node densities.

The rest of the paper is structured as follows: Related works are reviewed in Section 2. Theoretical foundations are discussed in Section 3. The proposed MAC protocol is given in Section 4. Section 5 expresses simulation results and finally, Section 6 concludes the paper.

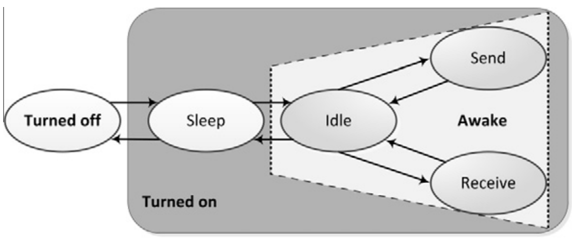


**Fig. 1.** Different modes of a sensor node in WSNs.

## 2. Related works

Chao and Lee [8] propose QMAC as a single channel MAC protocol for WSNs utilizing grid quorum to save energy. This protocol tries to prolong network lifetime by increasing node sleep time. However, using only a single channel in a network results in an increase in collision, therefore needing packet retransmission, which increases network energy consumption as well as latency. In addition, although QMAC proposes a method to assign different grid sizes to coronas in constant traffic rate, it is not obvious when and how grid sizes should be changed with traffic rate variations.

PW-MAC [41] is a receiver-initiated predictive wake-up MAC protocol in which every node computes its wake-up times using a pseudo-random wake-up schedule. Each node in PW-MAC periodically wakes up and broadcasts a beacon to announce that it is awake and ready to receive data. A sender has to know a receiver's pseudo-random generator parameters to wake up a little earlier than the receiver does and waits for a beacon. However, PW-MAC has some shortcomings so that each node has to send a beacon every time it wakes up regardless of whether any sender has data to send or not. In addition, protocol overhead increases as each node broadcasts its pseudo-random generator parameters periodically, which in turn worsens at higher network densities.

TMCP [28] is a tree-based multi-channel protocol for data collection applications. The main idea of TMCP is to partition the whole network into multiple vertex-disjoint sub-trees all rooted at a sink. Then, it allocates different channels to each sub-tree and forwards each flow along only its corresponding sub-tree. When a node wants to send information to the sink, it just uploads packets to the sub-tree that it belongs to. TMCP has some shortcomings. It is designed to support data collection traffic and it is difficult to have broadcasts due to its partitions. Aggregation cannot be employed since communication among nodes in different sub-trees is blocked.

EM-MAC [42] is a receiver-initiated multi-channel asynchronous MAC protocol proposed for WSNs. In EM-MAC, a sender rendezvous with a receiver by predicting the wake-up channel and wake-up time of the receiver. In EM-MAC, like PW-MAC, the sender knows the state of the receiver's pseudo-random function used to generate its wake-up channels and times. EM-MAC not only has the shortcomings of PW-MAC but also each node in EM-MAC