

# **Tone-Propagated MAC (TP-MAC): A Low Duty-cycle Low Latency MAC Protocol for Wireless Sensor Networks**

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**Abstract.** This paper presents Tone-Propagated MAC (TP-MAC), a novel MAC protocol for Wireless Sensor Networks (WSN)s, specially suited for early warning and tracking applications, where the traffic generated by sensor nodes (mainly alert messages) is sporadic but has stringent latency requirements. This protocol aims to maximize energy-efficiency while minimizing latency in source-to-sink and sink-to-source communication. This difficult objective is achieved integrating scheduled channel polling (i.e. synchronized low power listening) with rapid fast path establishment based on the propagation of short wake-up tones. An analytical model was used to compare TP-MAC with SCP-MAC. The results show that TP-MAC is able to achieve better target latencies even when its duty-cycle is lower during periods of inactivity. The results also show that the advantage of using TP-MAC increases with the hop-distance between source and sink.

**Keywords.** Wireless Sensor Networks, Early Warning and Tracking, MAC, Energy-Efficiency, Scheduled Channel Polling.



# Tone-Propagated MAC (TP-MAC): A Low Duty-cycle Low Latency MAC Protocol for Wireless Sensor Networks <sup>1</sup>

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## 1 Introduction

Wireless Sensor Networks (WSNs) have motivated intense research, in academia, industry and on the military sector due to the potential to support distributed micro-sensing in environments for which conventional networks are impractical or when the required sensor density demands a robust, secure and cost-effective solution. WSNs rely on large numbers of cheap devices, able to collaborate in distributed in-network data fusion and processing tasks, with final results that are equivalent to those obtained with centralized processing. An example of the latter is Homeland Security Early Warning and Tracking of Chemical, Biological Radiological, Nuclear and

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Explosive (CBRNE) agents, Toxic Industrial Materials (TIM), and other terrorist threats. In fact, this is generally regarded as one of the future WSN killer applications.

Homeland Security Early Warning and Tracking is one of the WSN application scenarios addressed in the FP6 IST project Ubiquitous Sensing and Security in the European Homeland (UbiSeq&Sens). The overall objective of UbiSeq&Sens is to provide a comprehensive architecture for medium and large scale WSNs, with the full level of security required to make them trusted and secure for all applications.

Homeland Security Early Warning and Tracking poses interesting requirements on the WSN networking aspects, namely the requirements for low duty cycles (in order to assure maximum autonomy and minimum maintenance) and low latency in source-to-sink alert notifications (in order to assure a timely response to CBRNE/TIM threats). Current WSN MAC protocols usually trade-off these two requirements, not supporting them simultaneously. The Tone-Propagated MAC (TP-MAC) protocol proposed in this paper tackles this problem, supporting ultra-low duty cycles in periods of no activity, and providing at the same time fast path establishment based on quick wake-up tone propagation in the beginning of activation periods.

The rest of this paper is organized as follows. Section 2 presents the WSN MAC protocols that were most relevant for this work. Section 3 presents TP-MAC. Section 4 presents a performance comparison between TP-MAC and SCP-MAC. Finally, section 5 concludes the paper.

## 2 Related Work

Many techniques and MAC protocols have been developed for WSNs, in order to lessen the sources of inefficiency in wireless access, such as idle listening, collisions, message overhearing and control packets overhead [1]. We will focus on scheduled contention-based protocols, and low-power listening, as they are more related to our work.

Contention-based protocols are more flexible than Time-division multiple-access (TDMA) protocols, because they can provide more flexibility in multi-hop communications, and are more prone to topologic changes. The IEEE 802.11 standard [2] was designed for wireless LANs and also for ad-hoc networks. In its Distributed Coordinated Function (DCF), it uses a contention protocol - Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), inherited from the MACAW protocol [3] – that has inspired some WSNs specific protocols, because it has satisfactory performance in avoiding collisions. Namely, the protocol messages sequence - RTS (Request to Send), CTS (Clear to Send), Data, and ACK (Acknowledge) - are used by other contention protocols

S-MAC [4] is a scheduled contention-based protocol. Nodes are active (listening and transmitting) for some time, and asleep for the remaining time of a fixed period. In the active time, it uses the basic ideas of the IEEE 802.11/MACAW contention protocol for data exchange. A technique, named *virtual clustering*, permits that nodes adopt and propagate time schedules that synchronize the active time of the nodes in the sensor network. SYNC packets are exchanged to keep the nodes schedules

synchronized and compensate for clock drifts. However, *virtual clustering* leads to existence of multiple schedules [5], because they are generated locally by the initiative of the nodes. This is somehow a source of inefficiency, because nodes at the frontier of more than a schedule have more active times. In [5] is also presented an algorithm to achieve a unique global schedule, but convergence is very slow (in the order of several minutes). Other techniques are used by S-MAC in order to avoid overhearing, and excessive control packets overhead (such as message passing).

S-MAC duty cycle, and therefore its energy efficiency, can be tuned by acting on the active time duration. However, its fixed cycle of operation is not flexible to adapt to different load conditions. Some protocols addressed this problem, namely T-MAC [6].

The basic idea of T-MAC, which mainly differentiates it from S-MAC, is that active time duration is not fixed, but finishes when no activation events (i.e., communication activity) in the media occur for a chosen timeout. However, as its authors note, T-MAC suffers from the *early sleeping* problem: briefly, in a chain of four nodes, if the first node wants to communicate till the fourth, through the second and the third, the third node can still ear the first communication (between the first and the second), and remain active, but the fourth node goes too early to sleep state. This is a major drawback, because in WSNs the communication is mainly oriented to the sinks, in chain communication patterns. The authors propose two solutions for this problem, but the first solution (a Future Request to Send packet, issued by the third node) seems only to be effective to maintain the fourth node awoken, and not for subsequent nodes. Consequently, T-MAC seems to have a latency problem.

In order to reduce the latency, the research team of S-MAC also proposes a *fast path algorithm* [5], with additional and staggered active times along the path, between a node and the sink. However, the fast path must be reserved hop-by-hop, in the first packet communication. *Adaptive listen* [7] is another technique described in the context of S-MAC. Nodes that ear neighbors protocol exchange messages, wake-up for a short time, after the full data transmission ends, to check if they have transmissions for them, instead of going to sleep till the next active time. Analysis and simulations show the effectiveness of this solution.

The Data-gathering MAC (D-MAC) protocol presented in [8] includes an adaptive duty-cycle like T-MAC. However, its main purpose is to minimize the node-to-sink latency in convergecast<sup>2</sup> networks, where all sensing data converges to only one sink node. D-MAC uses staggered synchronization so that a data packet heard by a node at one level of the tree in one slot is transmitted to the next level in the following slot. The node is then allowed to sleep until the reception slot for its level occurs again.

Another approach, different from the scheduled schemes, is low-power listening (LPL) [9], used by B-MAC [10], and by WiseMAC [11]. It is a very simple mechanism designed to minimize the energy spent in idle listening: receiving nodes periodically poll the media for activity, and if there is no activity, they return to sleep state for the rest of the period; the sender node can wake-up the receivers by sending a preamble. Poll durations can be very small, just the time to detect the preamble. However, preamble must last for an entire poll period, as nodes are not supposed to

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<sup>2</sup> Sometimes designated “reverse multicast”.

be synchronized. Nevertheless, this simple scheme can be effective in applications with low data traffic.

More recently, a new scheduled contention protocol was proposed. SCP-MAC (Scheduled Channel Polling MAC, [12]) combines the advantages of LPL and scheduled protocols. Nodes that have data to transmit contend in a first contention window for tone transmission; nodes that win the contention transmit a tone. Possible collisions in tone transmission are allowed, because what is important is the presence of the tone. The potential receiving nodes poll the media for short time (around 2-3 ms), just enough to detect the tone. If there is no tone, the receiving nodes return to the sleep state. If there is a tone, they remain woken up for a further data transmission. Actual data transmission can be done with a second contention window, only with the winners of the first contention window, and with RTS-CTS exchanges. Tone polls, and the tones themselves, are synchronized by the scheduled times, in the S-MAC way, and therefore can be very short. The long preambles of LPL are not needed. In this way, SCP-MAC proves to be much more efficient than LPL. Moreover, as contention is done in two consecutive windows, they can be smaller. Further use of adaptive listening in conjunction with SCP-MAC, is a hypothesis that the authors foresee. However, SCP-MAC presents a significant dependency between duty-cycle and transmission delay, since longer polling periods imply that the hop-by-hop transmission from sender to receiver also takes longer. This can be problematic in medium and large scale WSNs, specially in scenario that require the combination of ultra-low duty cycles with low latency transmission (e.g. long-term deployment of alarm-driven applications), which is the main problem addressed by TP-MAC.

### **3 Tone-Propagated MAC (TP-MAC)**

In order to achieve low duty cycle, the proposed TP-MAC protocol inherits some features from other MAC protocols, namely synchronized wake-up periods (S-MAC, SCP-MAC), and synchronized wake-up-tone announcement of data availability associated with scheduled channel polling (SCP-MAC). However, in TP-MAC the wake-up-tones are propagated across the WSN so that the nodes in the path from source to destination are woken-up as quickly as possible, before the arrival of the heralded data packets. In this way, TP-MAC is able to achieve low delivery latency even if the WSN node duty-cycle is extremely low, preventing or at least ameliorating the early-sleeping problem.

TP-MAC is based on the convergecast communication paradigm, assuming that the WSN is organized in a logical tree topology, associated with one sink, which corresponds to the root node. This imposes some cross-layer constraints on the network (i.e. routing) layer, which is not a real limitation, since most typical WSN scenarios require convergecast of sensor data towards sink nodes. Although there are several options to support more than one sink in TP-MAC, this paper only covers the basic algorithm, assuming that there is a single sink node. The support of multi-sink with TP-MAC is left for further study.

In a tree structure rooted at the sink node, it is possible to define different levels defined by the minimum hop distance relative to the sink node. In this way, the sink

node constitutes level 0 and the level number increases as hop distance to the sink node increases. The establishment of network levels is at the core of the wake-up-tone propagation mechanism.

TP-MAC establishes super-frame periods for channel access, each starting by a synchronization wake-up-tone and two wake-up-tone propagation windows (upstream and downstream), followed by a data transmission window (see Fig. 1). The size of the tone propagation window can be different for upstream and downstream, depending on the latency requirements. The channel access method in the transmission window can be based on any MAC protocol, e.g. CSMA/CA, S-MAC, T-MAC, SCP-MAC, etc.

The synchronization tone marks the beginning of the super-frame structure. This tone is periodically activated by the sink node and slowly propagated downstream to announce the transmission of a broadcast synchronizing/re-synchronizing SYNC packet in the data transmission window. The details of synchronization establishment/maintenance will not be explained in this paper due to space limitations.

The wake-up-tone propagation windows allow the announcement of data and establishment of fast paths from source to destination.

When no data traffic is generated, each node only has to poll the channel once in each wake-up-tone propagation window (only in the slot that corresponds to its level), and sometimes also in the synchronization slot. The nodes are allowed to sleep during the rest of the super-frame.

When a node has data to transmit, it first sends a wake-up upstream tone (e.g., for sensing data destined to the sink node), or a waking downstream tone (e.g., for control messages issued by the sink node to sensor nodes). The wake-up-tone propagation window structure guarantees that nearby nodes in the next upper/lower level listen to the generated wake-up-tone. They then propagate the tone upstream/downstream, as it can be seen in the tone propagation windows of Fig. 1. If a node detects a wake-up-tone in the last slot of a propagation window, then it shall only propagate it in the next super-frame. The tone propagation mechanism, which resembles the data propagation mechanism of D-MAC, assures that nodes within some hop distance are woken-up in just one operation cycle, forming a fast-path before actual data arrives. The maximum distance that a wake-up tone can reach in a single super-frame is equal to the number of tones in each tone propagation window, which is a configuration parameter.

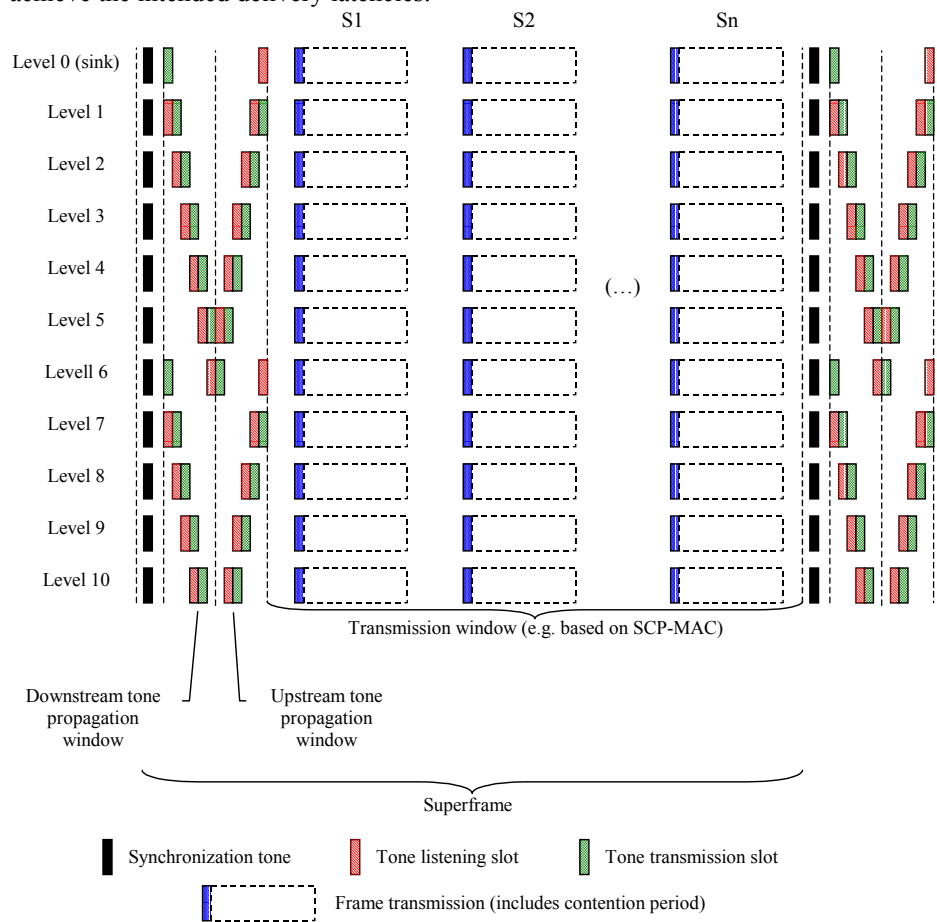
The nodes that form a fast path stay active in the data transmission window, for a pre-defined time interval, which is dimensioned to keep those nodes active until the announced data arrives. The timeout mechanism is similar to that defined in T-MAC.

TP-MAC nodes only poll the media for a number slightly above two times per cycle (two polls, respectively for upstream and downstream propagated tones in each super-frame, and more seldom for the synchronization/re-synchronization tone), propagating the wake-up tones fast and deeply through the network (and thus opening fast data transmission paths). In this way it is possible to achieve low latencies simultaneously with low duty cycles.

One side effect of the TP-MAC protocol is that downlink propagation of wake up tones may result in waking up all nodes of the network. This behavior is an advantage

when downstream data has to be broadcasted, and a handicap for other downstream traffic patterns. Nevertheless, if the applications do not demand stringent latency requirements for downstream traffic, the downstream tone propagation window can be eliminated and the synchronization slot can be also used for data announcements. The frequency of the synchronization tone can be configured as to match the required latency. This solution decreases the duty cycle even further.

Another side effect is that for the upstream tone propagation the nodes in adjacent branches of the tree at levels above the source may be also woken-up, since they also detect and propagate the wake-up-tones. This behavior can cause some energy inefficiency. However, it is compensated by the ultra-low duty cycle required to achieve the intended delivery latencies.



**Fig. 1.** TP-MAC super-frame structure and wake-up-tone propagation.

It should also be recalled that in both situations the nodes only stay awoken for a pre-defined time interval, switching back to normal channel polling if no traffic arrives. This also limits the impact of waking-up extra nodes.

## 4 Results

An analytical model was developed to compare TP-MAC with SCP-MAC, under the assumption that SCP-MAC is used by TP-MAC for data transmission. This model addresses the relationship between duty-cycle during periods of no traffic, and the minimum latency that can be achieved once the first packet of an active stream is generated. Fig. 2 shows the ratio between the duty cycles of TP-MAC and SCP-MAC as a percentage, for different numbers of hops, and different sizes of the wake-up tone propagation window. Other TP-MAC parameters are the following: number of transmission slots: 10; synchronization tone period: 5 cycles. It is worth to note that TP-MAC duty cycle decreases with increasing number of hops, but its energy efficiency gain with respect to SCP-MAC stabilizes for high numbers of hops. It is also shown that higher number of tones can give higher energy efficiency gain. For instance, for 10 tones, we can obtain a duty cycle as low as 22% of the SCP-MAC duty cycle, for large network sizes.

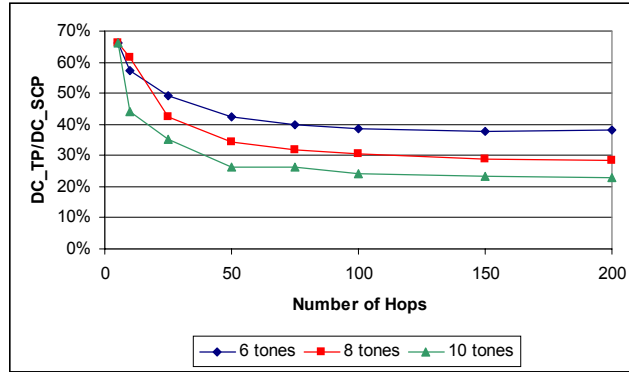


Fig. 2. Ratio between the duty cycles of TP-MAC and SCP-MAC as a function of the number of hops and the size of the wake-up-tone propagation window.

## 5 Conclusions

This paper has presented Tone-Propagated MAC (TP-MAC), a novel MAC protocol for WSNs, specially suited for early warning applications, where the traffic generated by sensor nodes (mainly alert messages) is sporadic and has stringent latency requirements. TP-MAC uses a multicast/convergecast tree WSN topology, which is used for fast data path establishment, propagating short wake-up-tones upstream and/or downstream between adjacent tree levels. Unlike other fast-path establishment mechanisms, TP-MAC tone propagation does not incur on latency penalty for the transmission of the first packet of a stream. It provides some degree of decoupling between latency and duty-cycle, i.e. it allows TP-MAC to achieve lower duty-cycles in periods of inactivity without compromising the target latency. The reliance on a

logical tree topology is not a big limitation from the point of view of the authors, since it is typical in most WSN applications.

Results obtained with an analytical model that compares TP-MAC with SCP-MAC clearly show that TP-MAC can achieve much lower duty cycles for the same target latency, or equivalently, very low latencies for the same duty cycles. This advantage tends to increase with the length of the path, and stabilizes for more than 50 hops. The analytic model was derived for the quiet state, as we believe that is the most common network state in many WSN applications. However, simulations and further development of the analytical model must still be done, in order to compare TP-MAC and SCP-MAC duty cycles and latencies in other realistic scenarios, with increased contention and inter-flow interference.

The support of multiple sink nodes is another essential requirement of most homeland security early warning and tracking applications, as it greatly increases network robustness and availability. The authors are currently evaluating alternative schemes to support multiple sinks in TP-MAC.

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