BoX-MACs: Exploiting Physical and Link Layer Boundaries in Low-Power Networking

David Moss
Rincon Research Corporation
101 N. Wilmot, Suite 101
Tucson, AZ 85711
dmm@rincon.com

Philip Levis
Computer Systems Laboratory
Stanford University
Stanford, CA 94305
pal@cs.stanford.edu

Abstract

We present two MAC layers for ultra-low-power wireless networking, BoX-MAC-1 and BoX-MAC-2. Leading low-power MACs today reside in a single layer: BMAC exploits only the physical-layer while XMAC utilizes only the link-layer. In contrast, BoX-MAC-1 and BoX-MAC-2 are cross-layer protocols. BoX-MAC-1 incorporates link-layer information into a predominantly physical-layer sampling approach. BoX-MAC-2 combines physical-layer information into a predominantly link-layer packetized approach. Through analysis and experiments on CC2420-based platforms, we find these cross-layer protocols consume up to 40-50% less energy than XMAC and 30% less energy than BMAC under reasonable workloads. Furthermore, BoX-MAC-2 yields up to 46% more throughput than its XMAC counterpart. Together, BoX-MAC protocols provide a comprehensive set of low-power link-layer primitives for a wide range of network workloads. The advantages of these cross-layer MAC designs over single-layer approaches provide insight on requirements for future radio chip and platform designs.

1. Introduction

Low power MAC layers are the most heavily studied area of wireless sensornets: at first glance, it seems there is at least one protocol for each letter in the alphabet. Despite this surfeit of options, networks tend to use one of three protocols: SMAC [20], BMAC [17], or XMAC [13]. Each of these protocols operates at a single layer: SMAC uses link-layer scheduling, BMAC uses physical-layer carrier sensing, and XMAC uses link-layer wakeup packets. Confining their logic to a single layer keeps each protocol simple yet effective.

Experience has shown, however, that cross-layer designs can be much more efficient than their single-layer cousins [16, 10]. Section 2 discusses these existing single-layer and cross-layer protocols in depth. The ability to simultaneously use information from multiple layers of the protocol stack allows them to make better decisions. Despite these advantages, networks today use single-layer MAC protocols; simplicity's benefit outweighs the cost to efficiency.

This paper explores this tension between simplicity and efficiency. Section 3 proposes two cross-layer MAC protocols. The first, BoX-MAC-1, uses a predominantly layer 1 (physical) low power mechanism, but incorporates a very small amount of layer 2 (link) information: rather than transmit a wakeup preamble, as BMAC does, BoX-MAC-1 continuously transmits a data packet. This continuously packetized wake-up transmission allows BoX-MAC-1 nodes to save energy by only staying awake for packets destined to them. Other tangential effects of accessing layer 2 information include better support for mobile nodes and resilience to Denial of Sleep [12] attacks.

The second, BoX-MAC-2, uses a predominantly layer 2 low power mechanism, but incorporates a very small amount of layer 1 information: rather than waking up long enough to hear a complete packet, as XMAC does, it first examines whether there is energy on the channel. Including physical-layer sampling into BoX-MAC-2 diminishes receive check lengths by a factor of 4.

Section 4 evaluates the improvement this small amount of cross-layer information flow can bring. Compared against BMAC, the dominant low-power MAC that uses a layer 1 mechanism, BoX-MAC-1 is always more efficient and can reduce energy consumption by as much as 30%. Compared against XMAC, the dominant low-power MAC that uses a layer 2 mechanism, BoX-MAC-2 is always more efficient and can reduce energy consumption by as much as 50%. Which protocol is more efficient – BoX-MAC-1 or BoX-MAC-2– depends on network density, expected

workload, and network duty cycle. Generally, BoX-MAC-1 is more efficient for high volatility networks with little traffic, and BoX-MAC-2 is more efficient in low volatility networks with lots of traffic. Both BoX-MAC-1 and BoX-MAC-2 have been heavily used and tested: versions of them are part of the low-power CC2420 stack in TinyOS 2.0.

This paper makes three research contributions. First, it proposes two novel low-power MAC protocols that use very limited cross-layer information: BoX-MAC-1 and BoX-MAC-2. Second, through a series of models and experiments, it quantifies the benefits this cross-layer information has over the closest single-layer protocol counterparts: 30-50%. Third, by examining both protocols side by side with their counterparts, it provides a comprehensive evaluation of the tradeoffs of different low-power MAC approaches, including an independent comparison of XMAC and BMAC. While many papers have proposed a variety of MAC solutions and many techniques in BoX-MAC protocols are present in commercial and research stacks today, this paper represents the first comprehensive evaluation of the tradeoffs between these different approaches. Together, these results are evidence of the utility of chip-level RF mechanisms, such as channel energy detection, preamble sampling, and cyclic transmission, thereby providing guidance on future platform design.

2 Background

Low-power MAC layers generally fall within two categories: *asynchronous* and *synchronous*. Synchronous low-power networks that communicate on local- or network-wide schedules are interesting, and the history of these protocols is pointing more often toward a hybrid approach. SMAC and TMAC are examples of early adopting, pure TDMA (time-division multiple access) protocols, simultaneously activating each node's radio to attempt communications [20, 19]. As other sources have already indicated [18], TDMA protocols suffer from many deficiencies when applied to ad-hoc wireless networks. Network scalability, mobility, efficiency, broadcasting capabilities, and robustness often severely degrade in performance due to the rigidity of pure TDMA protocols.

Other hybrid synchronous protocols, such as WiseMAC [14], SCP-MAC [21], and ZMAC [18], attempt to bridge the deficiencies of TDMA by combining TDMA with certain types of asynchronous support. WiseMAC, for example, combines asynchronous channel sampling with scheduled transmissions. SCP-MAC is one which transforms asynchronous protocols into synchronous communications by aligning the time at which receive checks are performed. ZMAC combines TDMA time slots with receive check functionality derived from asynchronous protocols, increasing fairness and channel utilization. All three synchronous protocols, utilizing some degree of asynchronous functionality, may benefit from advances on the asynchronous side of low-power communications.

Asynchronous driven low-power protocols have been very common in current ad-hoc wireless sensor network deployments. After all, asynchronous networks are quick to form, reliable, low-power, scalable, widely tested, and are often not very complex. While the synchronous protocols are heavily impacted by clock drift and temperature variations [11], asynchronous protocols experience no such effects. These asynchronous protocols are typically implementable on low cost microcontrollers, offering a competitive advantage over synchronous duty cycling.

BMAC [17] is one of the first successful asynchronous radio duty cycling strategies which utilizes purely physical-layer information to achieve low-power operations. The use of layer 1 requires B-MAC driven nodes to remain awake throughout the duration of long-preamble transmissions before obtaining useful packet information. Meanwhile, XMAC [13] acquires only link-layer information in its approach to channel sampling. This exclusive layer 2 approach offers XMAC the ability to end wake-up transmissions twice as fast as BMAC through the use of early acknowledgements, but XMAC's packet-based receive check lasts more than 20 times longer than a single BMAC receive check.

BMAC was originally realized on a TI/Chipcon CC1000 [2] byte radio and XMAC was geared for the TI/Chipcon CC2420 [3] packet radio. The CC2420 radio, available on widely used ad-hoc networking platforms [4, 5, 8], offers several advantages over its CC1000 predecessor. First, it is built around the IEEE 802.15.4 standard [9], allowing a microcontroller to upload and download full packets of information at a time. The radio aids CSMA (carrier-sense multiple access) [15] protocols by providing a Clear Channel Assessment (CCA) pin to automatically indicate channel activity. It also provides other readily available features to the microcontroller including a Start Frame Delimiter (SFD) pin to denote the beginning and end of a transmission, and automatic preamble and CRC generation. Furthermore, the radio switches to receive mode on its own between each packet transmission. Although this simplifies code in the microcontroller, Rx / Tx switching adds roughly 192 μs delay in each direction causing gaps to appear in the modulation spanning multiple transmissions. The amount of automation built into the CC2420 hindered early attempts to implement layer 1 low-power protocols such as BMAC. XMAC, in response, applied layer 2 low-power strategies in attempts to circumvent those obstructions.

Wireless protocols already greatly benefit from cross-layer designs, taking into account adverse properties such as mobility and interference in the development of higher layers. In this manner, wireless networks do not fit well with

the layered design approach exhibited by most wired networks. Applying these principals to low power communications, we hypothesize that a unified, cross-layer approach which incorporates information flow from both physical- and link-layers will increase efficiency and throughput while maintaining similar reliability as previous layer 1 and layer 2 low-power attempts.

We look to synthesize the two approaches of XMAC and BMAC by first establishing how the physical- and link-layer characteristics of each implementation were most valuable in reducing radio on-time. From this, we can derive a minimum set of radio features that must be present to support the successful implementation of cross-layer low-power communications.

2.1. BMAC

Polastre et. al. [17] created one of the first widely successful asynchronous low-power implementations known as BMAC. BMAC utilizes pure physical-layer information from the radio to quickly detect and wake up from nearby transmitters during one of its periodic receive checks. To actually perform a receive check, nodes simply reverse the role of clear channel assessments which are typically intended to be used in multiple access CSMA [15] protocols. These integrated clear channel assessments allow nodes to rapidly return to deep-sleep if no neighboring wake-up transmissions are detected on the channel

To overlap with the periodic layer 1 receive checks, BMAC transmitters are obligated to send packets using long, bit-stream preambles. These preambles wake up each node within proximity of the transmitter, whether or not a particular node is the destined recipient of the packet. After waking up, all BMAC receivers must remain active in receive mode expending energy throughout the duration of the long-preamble wake-up transmission before acquiring the packet. This results in a well-known overhearing problem [13] which makes BMAC extremely susceptible to Denial of Sleep [12] attacks by unintelligent rogue transmitters. BMAC's physical-layer receive checks are attractive, but its lack of link-layer input can be detrimental to a network's aggregate energy consumption.

2.2. XMAC

XMAC [13], implemented by U.C. Boulder, attempts to solve some of the problems with BMAC on packet based radios by applying link-layer information into its low-power mechanism. XMAC's layer 2 receive check strategy leaves the radio in receive mode long enough to detect the presence of small wake-up packets sent by neighboring transmitters. These packet-based receive checks require XMAC to leave radios enabled for nearly twice the amount of time required for a transmitter to send a single wake-up packet. This hindrance can be rather significant when taking into account CSMA backoffs [15], acknowledgement wait periods, and transmission delays.

As an improvement over BMAC, the acknowledgement period between each wake-up packet allows XMAC to cut its packetized wake-up transmissions by an average of 50%. Therefore, the penalty for a layer 2 XMAC transmission with early acknowledgements is much less than the penalty for a layer 1 BMAC style transmission. This allows multiple XMAC transmitters to share a channel more fairly.

Unfortunately, the packets within XMAC's wake-up transmission consist only of 802.15.4 headers [9], requiring handshakes to deliver the final payload within a separate packet. Consequently, this reduces XMAC's maximum possible throughput by nearly half.

3. Design

The efficiency and robustness of asynchronous low-power communications can be improved by sharing a small amount of physical- and link-layer information in the radio duty cycling functionality. Throughout this section, Figure 1 helps to visually understand the differences between each protocol.

3.1. BoX-MAC-1

BoX-MAC-1 improves upon BMAC by adding link-layer information to the long wake-up transmission. To actually add this link-layer information, we replace BMAC's bit-stream preamble and with a *continuously packetized* wake-up transmission, noted by the feature comparisons in Table 1. This addition helps to prevent nearby nodes from waking up unnecessarily when detecting wake-up transmissions destined for other neighbors. Put another way, this is a solution to BMAC's overhearing problem.

In addition to solving BMAC's overhearing problem, the inclusion of layer 2 information within BoX-MAC-1's wake-up transmission allows transmitters to sleep during

Table 1. Although BoX-MAC-1 and BoX-MAC-2 appear to have similiar features, BoX-MAC-2 actually accesses more Layer 2 functionality than BoX-MAC-1.

	Receive Check	Tx Wake-up
BMAC	Layer 1	Layer 1
BoX-MAC-1	Layer 1	Layer 2
XMAC	Layer 2	Layer 2
BoX-MAC-2	Layer 1	Layer 2

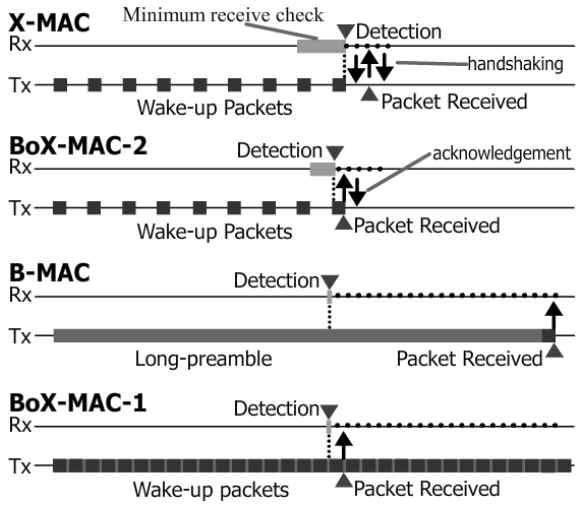

Figure 1. Visual comparison of the transmission strategies and receive checks between XMAC, BMAC, BoX-MAC-1 and BoX-MAC-2.

times of channel congestion. In any CSMA enabled network, a single transmitter must secure the channel within its geographical region before beginning a transmission. Typically, a node laying claim to the channel must first determine that no other transmitters are utilizing the resource. In CSMA, this is done through the use of clear channel assessments coupled with short, randomized backoff periods. While performing CSMA backoffs and waiting for the channel to become available, the radio normally remains active and consuming energy. In BMAC this wait period can be significant, not only because wake-up transmissions are very long but also because nodes waiting to transmit on the channel cannot know if the current transmission is destined for them. Therefore, BMAC nodes must remain awake and listening while other transmitters monopolize the channel. BoX-MAC-1, in contrast, has the ability to determine if the current wake-up transmission on the channel is destined for a particular node. This allows BoX-MAC-1 transmitters waiting for access to the channel to turn their radios off in an *extended backoff* period.

The concept of an extended backoff is simple: it's a much longer CSMA backoff period where the radio is disabled between channel assessments. As in any CSMA scheme, randomizing extended backoff periods allows the channel to be shared more fairly amongst several nodes [15].

Due to the dynamic complexity of extended backoffs and their varying performance across network parameters, the optimal extended backoff period has not yet been determined and its effects have not been quantified into equations. Our BoX-MAC-1 implementation randomizes its extended backoff period on the order of a few hundred milliseconds. This magnitude seemed like a good trade between channel utilization and node energy savings, especially for receive check intervals around one second. Further characterization may determine if a better magnitude exists, and we expect that an extended backoff randomized to within some fraction of the network's receive check interval will work best. Section 4.3 will discuss the improved efficiency observed by the use of extended backoffs in BoX-MAC-1.

We compare equations representing radio on-time to determine how the inclusion of a layer 2 continuously packetized wake-up transmission improves a predominately layer 1 low-power scheme. First, the amount of time spent transmitting a BMAC packet is described in Eq. 1, requiring each neighboring node to stay awake receiving that packet for the average amount of time defined in Eq. 2. Note that the duration of a preamble, $t_{preamble}$, is always slightly greater than the sleep period between layer 1 receive checks. This is typically several orders of magnitude larger than both the backoff and packet transmission durations, which may be quite substantial.

$$t_{Tx}(bmac) = t_{backoff} + t_{preamble} + t_{packet} \quad (1)$$

$$t_{Rx}(bmac) = \frac{t_{preamble}}{2} + t_{packet} \quad (2)$$

By receiving the final packet from BoX-MAC-1's packetized wake-up transmission early, the minimum time required to receive a packet is reduced from BMAC's prodigious Eq. 2 to BoX-MAC-1's Eq. 3, where t_{wakeup} is a trivial delay experienced before the next coherent packet arrives.

$$t_{Rx}(box1) = t_{wakeup} + t_{packet} \quad (3)$$

Two methods may achieve the continuously packetized wake-up transmission of BoX-MAC-1 on packet radios. The first and most basic technique is to simply disable all parameters that would lead to delays in packet retransmissions. To increase the rate of wake-up packet retransmissions, CSMA backoffs are disabled after carefully acquiring the channel, and acknowledgements are postponed until the end of the wake-up delivery. To eventually obtain an acknowledgement, the last packet in the wake-up transmission is sent with its acknowledgement request flag enabled. Gaps in modulation may remain between each packet due to Rx / Tx switching characteristics of the radio and SPI bus retransmit commands, causing the layer 1 receive checks and channel acquisition time to increase slightly.

The second method to attain a continuously packetized wake-up transmission is to enable a test mode on the radio which will continuously retransmit the contents of the TX FIFO. On the CC2420, this type of continuous modulation is achieved by modifying the TX_MODE setting in

the MDMCTRL1 register [3]. The Atmel AT86RF230 radio may continuously modulate the channel by toggling its TST mode input pin [1]. While the latter continuous modulation method is available on the CC2420, our reference design employed the basic retransmission technique to evaluate BoX-MAC-1's expected performance across packet-based radios that may not support infinite transmission capabilities. Both implementations require duplicate packet filtering to operate, and we employ the Data Sequence Number (DSN) byte and source address in the 802.15.4 header for this purpose.

BoX-MAC-1's layer 1 receive check is implemented on the CC2420 by activating the radio in receive mode and sampling its CCA pin. This pin is sampled a nominal amount of times to ensure any activity on the channel is not the result of spurious noise, and to bridge the small gaps between wake-up packets resulting for Rx / Tx switching. After detecting a transmission, the radio wakes up for a longer period to attempt to acquire a frame. When a valid frame is finally acquired, the radio remains active as long as subsequent communications are taking place in a timely manner. If no communication occurs within a 50 millisecond period, the radio returns to deep-sleep similar to the TMAC protocol [19].

3.2. BoX-MAC-2

Recall from Section 2.2 that XMAC utilizes a layer 2 packet-based receive check. This use of layer 2 couples the size of XMAC's receive check to the duration of the packet attempting to be detected. Decreasing the size of the layer 2 receive check requires the transmitter to send smaller wake-up packets, which forces XMAC to send only the vital 802.15.4 header information within its packetized wake-up transmission.

Replacing XMAC's packet-based receive check with a layer 1 energy-based receive check decouples the size of an individual receive check from the length of a wake-up packet. No longer should we be worried about transmitting the smallest possible wake-up packet in BoX-MAC-2 as we did with XMAC; instead, we're attempting to detect the presence of energy. The decoupling between packet size and receive check duration allows BoX-MAC-2 to replace XMAC's dummy wake-up packets with the final deliverable packet. As a result, no handshaking is required in BoX-MAC-2 to obtain the intended payload, and throughput can nearly double XMAC's. While both radios are awake, subsequent packets are delivered to the recipient at maximum throughput. Put another way, multiple packets can be communicated bidirectionally after a single receive check detection.

To increase the probability of detecting energy on the channel in BoX-MAC-2's layer 1 receive check, the gaps in modulation between each packet in a wake-up transmission must be reduced as much as possible. There are four main elements that add to these gaps in modulation. First, CSMA backoffs play a large role in the amount of time between individual packets. While CSMA backoffs are not removed entirely in BoX-MAC-2, their duration is diminished which allows several transmitters to share the channel. Second, acknowledgement periods add to the gaps in modulation between wake-up packets. Assuming a wake-up transmission is not destined for the broadcast address, the inclusion of a quiet period reserved for an early acknowledgement for each wake-up packet allows a transmitter to cut the length of its wake-up transmission by an average of 50%. Although Table 1 appears to show BoX-MAC-1 and BoX-MAC-2 have the same set of layered features, the use of layer 2 early acknowledgements in BoX-MAC-2 is a key differentiator from BoX-MAC-1's implementation. Third, inherent Rx / Tx switching of the radio adds time between transmissions. On the CC2420 radio, the Rx / Tx switching time is about 192 μs in each direction. Finally, the microcontroller must issue commands over the SPI bus to retransmit each packet, which adds further delays.

To analytically compare XMAC with BoX-MAC-2, Eq. 4 defines the amount of time required for an XMAC receive check to detect the presence of a nearby transmitter. Due to the constraints of a layer 2 receive check, this amount of time is nearly twice the duration of a single packet transmission.

$$t_{RxCheck}(xmac) = t_{backoff} + 2t_{packet} + t_{ack} \quad (4)$$

Switching XMAC's layer 2 receive check to BoX-MAC-2's layer 1 energy check reduces the minimum receive check duration from Eq. 4 to Eq. 5, removing the dependency on packet size.

$$t_{RxCheck}(box2) = t_{backoff} + t_{ack} \quad (5)$$

There are two possible methods to perform this type of layer 1 receive check on a packetized layer 2 wake-up transmission. The first method is to activate the CC2420 radio and poll its CCA pin enough times to span the duration of Eq. 5. The second method is to enable the CC2420 radio, start a high speed timer, and wait for an interrupt on the CCA line. The initial versions of BoX-MAC-2 employ the polling method.

3.3. Network Performance

Two primary factors affect the performance of BoX-MAC protocols in a network: volatility and traffic. Volatility in a low-power communications sense refers to how quickly packets can be delivered from node to node. As a network performs more receive checks, its volatility increases. Traffic refers to how many transmissions are taking

place within RF range of each node in the network. To assess which BoX-MAC protocol might work best for a given network type, we decompose the various events which affect radio activity and compare the approximate radio on-time between each protocol. XMAC and BMAC are included in these equations to further weigh the effectiveness of BoX-MAC protocols versus their contenders.

Each node in a given network spends a certain amount of time per day performing idle receive checks without detecting any valid or invalid transmissions. Equations 6, 7, and 8 compare the amount of time allocated to these types of idle receive checks from the viewpoint of a single node in the network, where R is the total number of receive checks per day. The constant multiplier in these equations refers to the duration of a single receive check in milliseconds. For BoX-MAC protocols, these durations are described further in Section 4.

Note that BoX-MAC-1 currently does not shorten the duration of any wake-up transmission below the length of a single receive check period. As a consequence, the number of transmissions and receptions per day is typically limited by the number of receive checks per day. In the future, allowing BoX-MAC-1 to realize when a neighbor has recently been awakened will allow it to communicate at maximum throughput for subsequent packet deliveries, emulating the behavior of BoX-MAC-2.

$$t_C(box1, bmac) = R \cdot (0.78\,[ms]) \tag{6}$$

$$t_C(box2) = R \cdot (5.61\,[ms]) \tag{7}$$

$$t_C(xmac) = R \cdot (20\,[ms]) \tag{8}$$

Next, each node in the network spends a certain amount of time acquiring both valid and invalid packets. The average time per day consumed in each protocol for the acquisition of valid packets is expressed in Eq. 9 and 10, where T is the period between receive checks in milliseconds and V is the number of valid packet receptions per day.

BoX-MAC-2 and XMAC have the potential of receiving or transmitting multiple packets within a single receive check while radios remain active. This energy saving effect is not taken into account in any equations due to its complexity with varying network parameters.

$$t_V(box1, bmac) = V \cdot \left(\frac{T}{2} + (50\,[ms])\right) \tag{9}$$

$$t_V(box2, xmac) = V \cdot (50\,[ms]) \tag{10}$$

The time spent acquiring invalid packets belonging to other nodes in Eq. 11 is identical between BoX-MAC-1, BoX-MAC-2, and XMAC. The variable I in this equation represents the number of invalid packet receptions per day seen by a single node. BMAC's layer 1 preamble transmission brings out its overhearing problem in Eq. 12. This is a significant departure from efficiency when compared to Eq. 11.

$$t_I(box1, box2, xmac) = I \cdot (20\,[ms]) \tag{11}$$

$$t_I(bmac) = I \cdot T \tag{12}$$

Finally, each node spends some amount of time transmitting, described by Eq. 13 and 14 where D is the number of wake-up transmission deliveries per day. Again, BoX-MAC-2's ability to deliver several packets during a single receive check is not accounted for in these equations.

During transmissions, BoX-MAC-1 has an added advantage over BMAC from the use of its extended backoff periods. We do not attempt to analytically express the amount of energy saved through the use of BoX-MAC-1's extended backoffs, simply because the evaluation is complex. Also, we do not attempt to quantify the amount of extra energy consumed during the many channel assessments that may take place while waiting for the channel to become available. The exclusion of this complicated portion of the analysis could have two effects. First, for congested networks, the extended backoff will largely save energy over BMAC, and will cause the calculated energy consumption to appear too high. Second, networks with longer wake-up transmissions will require other transmitters to perform more channel detections while waiting for a clear channel. This type of channel sampling will increase the actual energy consumption over predictions simplistic equations can produce.

$$t_X(box1, bmac) = D \cdot T \tag{13}$$

$$t_X(box2, xmac) = D \cdot \left(\frac{T}{2}\right) \tag{14}$$

Each protocol's performance in a network can be compared by combining their parameters into Eq. 15. The protocol yielding the most efficiency for a given network profile will have the least radio on-time per day. Obviously, an on-time result greater than the amount of time in a day means the radio is active 100% of the time, and throughput may suffer as a consequence.

$$t_{on/day} = t_C(x) + t_V(x) + t_I(x) + t_X(x) \tag{15}$$

Reflecting on these approximations, the BoX-MAC-1 implementation has extremely efficient layer 1 receive check method in Eq. 6. This will outperform BoX-MAC-2 for high volatility networks exhibiting many receive checks per day. The BoX-MAC-2 protocol, in contrast, is able to cease its layer 2 wake-up transmissions early in Eq. 14. This makes BoX-MAC-2 more efficient for networks with higher amounts of traffic. BoX-MAC-2's inefficient receive check in Eq. 7, however, necessitates the use of a low volatility network with fewer receive checks per day.

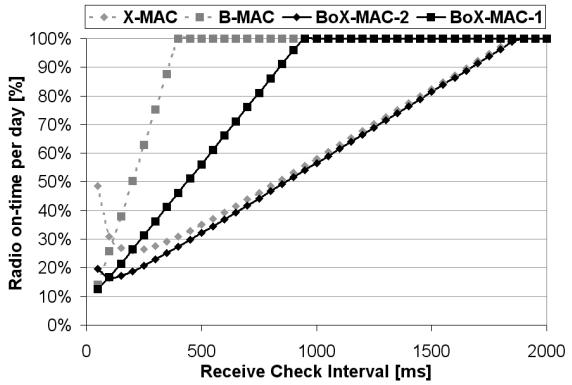

Figure 2. Computational analysis of a high traffic network profile.

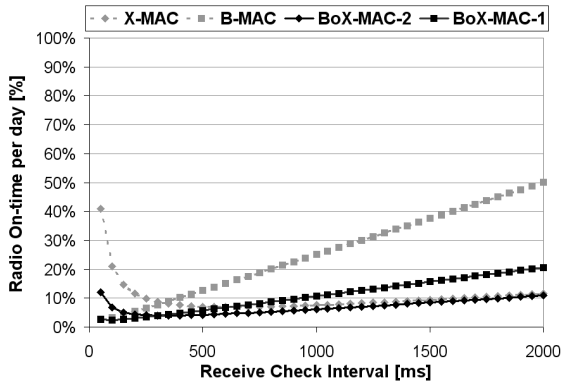

Figure 3. Computational analysis of a low traffic network profile. Note the intersections in protocol efficiency near the 300 ms receive check interval.

3.4. Analytical Models

We use the equations derived in Section 3.3 to model two network profiles predicting the performance of BoX-MAC-1 and BoX-MAC-2. Each virtual network in this analysis consists of 3 transmitters sending unicast messages to a single receiver. This type of network was chosen to effectively emulate part of a collection tree where one receiver might have multiple children. These network setups are also reproducible to perform actual measurements.

The first analysis in Figure 2 profiles a high traffic network sending one unicast packet per second from each of the three transmitters. This amount of traffic is abnormally high for an actual deployment, but will serve to accentuate the benefits of some protocols, namely BoX-MAC-2. The interval between receive checks in this high traffic network is varied from 50 to 2000 milliseconds to demonstrate how the number of receive checks per day, and thus the duration of wake-up transmissions, affects energy consumption.

As depicted in Figure 2, BoX-MAC-1 is more efficient than BMAC and BoX-MAC-2 is more efficient than XMAC because their radios are on for less time per day. BoX-MAC-1 is mostly inefficient because there are many transmissions occurring in this network profile. BoX-MAC-2, in contrast, excels in networks with higher traffic.

There are three characteristics notably absent from Figure 2. First, while BoX-MAC-1 eventually reaches 100% radio on-time per day, the inclusion of an extended backoff should ultimately prevent this from occurring. Next, BoX-MAC-2's ability to nearly double the amount of throughput over XMAC is expected to somewhat decrease its radio on-time per day. Finally, BoX-MAC-2 and XMAC are actually able to receive multiple packets within a single receive check, which will decrease energy consumption in reality.

To the left side of Figure 2, the period between receive checks is small. This results in an extraordinary number of receive checks occurring each day, and their efficiency is the dominating factor in network energy consumption. The predominately layer 2 protocols, BoX-MAC-2 and XMAC, suffer with an increase in the rate of receive checks. This is denoted by their higher radio on-time at the 50 ms receive check interval. The predominately layer 1 protocols, BoX-MAC-1 and BMAC, are very efficient at these smaller receive checks intervals. This makes BoX-MAC-1 and BMAC more desirable than layer 2 protocols in the instance.

Wake-up transmissions are the dominating factor on the right side of Figure 2. Because layer 2 protocols such as BoX-MAC-2 and XMAC can cut the duration of their wake-up transmissions in half, they exceed the efficiency of the layer 1 BoX-MAC-1 and BMAC protocols. Furthermore, BoX-MAC-2's throughput advantages over XMAC will increase its efficiency, especially where transmissions dominate energy consumption.

The second model in Figure 3 profiles a low traffic network sending one unicast packet every ten seconds from each of the three transmitters. In an actual network deployment, even this amount of traffic may be too high. We choose this parameter to increase the rate at which actual network measurements could be performed for comparison while demonstrating the effectiveness of BoX-MAC-1 at lower traffic rates.

As with the high traffic case, this low traffic network depicts BoX-MAC-1 and BoX-MAC-2 are still more efficient than BMAC and XMAC, respectively. When the receive check period of this network is set below approximately 300 milliseconds, receive check efficiency dominates and BoX-MAC-1 is most efficient. Above 300 milliseconds, wake-up

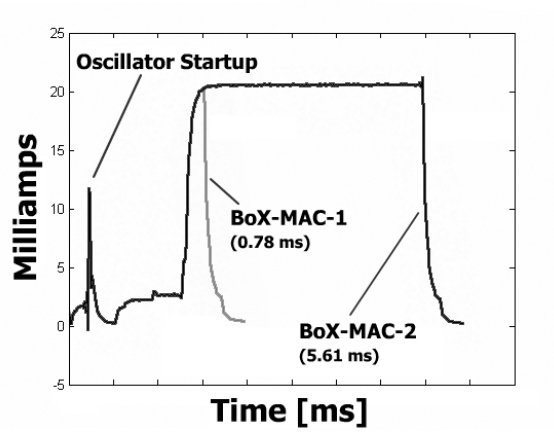

Figure 4. BoX-MAC-1 and BoX-MAC-2 transient receive checks, depicting the difference in magnitude between sampling durations for each protocol.

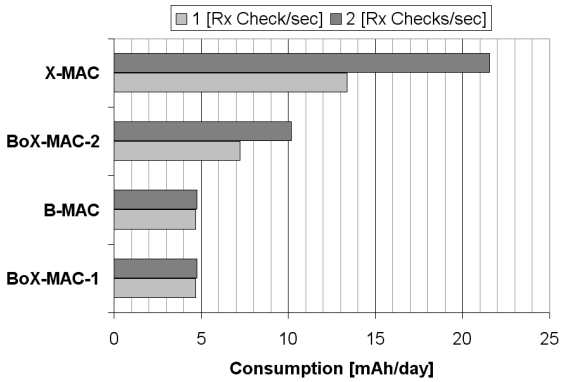

Figure 5. Receive check energy consumptions on a single node. BoX-MAC-2 exhibits twice the efficiency of XMAC, and layer 1 receive checks are much more efficient than layer 2 driven protocols.

transmission durations begin to dominate the equations and BoX-MAC-2 becomes most efficient.

4. Evaluation

In this section, we measure and evaluate the energy consumption, throughput, and reliability of the cross-layered BoX-MAC protocols against BMAC and XMAC implementations.

The evaluation of energy consumption is broken into two parts. First, we measure the consumption of a single node performing idle receive checks while running BoX-MAC protocols, determining which protocol has the most efficient detection scheme. Observations from Denial of Sleep attacks are also discussed. Next, the energy consumption of two small networks consisting of three unicast transmitters and one receiver is evaluated, providing actual results to compare against the network profile models from Section 3.4. We show the models and equations are a good approximation of network performance ratios, with some anticipated deviations from reality.

Throughput is evaluated using two test setups. The first test evaluates throughput on a network level, where BoX-MAC-2 is demonstrated to handle increasing channel contention and throughput better than BoX-MAC-1. The second throughput test compares the maximum node-to-node throughput across all protocols, and BoX-MAC-2 sees 46% more throughput than XMAC.

Reliability is tested in a network setting. Here, we look to find correlations between channel contention and the probability a packet will be delivered successfully. We also discuss the effects of mobility on layer 1 protocols.

4.1. Methodology and Implementation

To gather fine granularity power measurements, voltage probes from a 24-bit, 50 kSps data acquisition system were connected across a 1-ohm precision resistor placed in series with a 3.0V power supply and the device under test. A combination of Python and Matlab scripts post-processed the raw data, extracting power consumption measurements and integrating them to units of milliamp-hours per day. This unit of measurement is useful for determining the expected lifetime of a node given its battery's milliamp-hour rating.

To provide a basis for comparison, we implemented XMAC and BMAC on the CC2420 under TinyOS 2.x [7]. BMAC's long preamble was attained using the CC2420's infinite retransmission test mode to transmit packets with invalid CRCs. These invalid CRCs allow the stream of data to appear as non-packetized information at the receiver. BMAC receivers wake up by sampling the CCA pin to detect channel energy, and wait until a preamble transmission completes before obtaining the valid packet at the end.

The XMAC receive check method turns on the radio and sets a short timeout timer which is configured to allow the radio to perform quick and reliable layer 2 packet detections. In agreement with XMAC's original implementation [13], we were not able to reliably set the duration of this layer 2 receive check below 20 ms. XMAC's packetized wake-up transmission is optimized for performance by only transmitting the necessary 802.15.4 header information [9]. Reception of the final XMAC data packet occurs only after a handshake with the transmitter.

All measurements were performed using Tmote SKY [4] modules without DMA support [6].

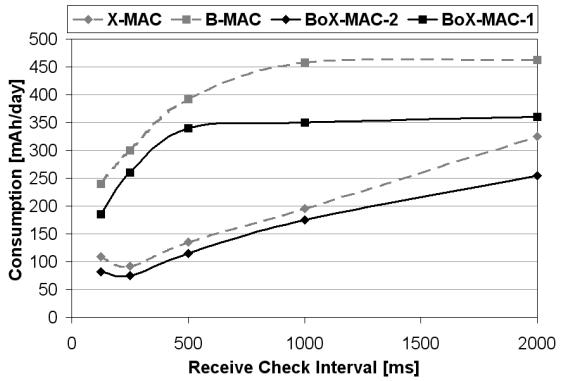

Figure 6. Measured energy consumption of a single node in a high traffic network.

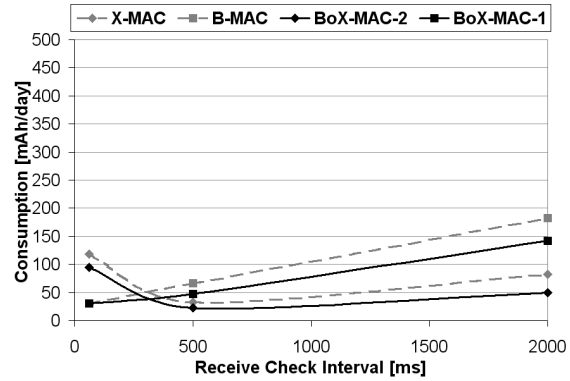

Figure 7. Measured energy consumption of a single node in a low traffic network. Note the intersections in protocol efficiency near the 300 ms receive check interval.

4.2. Receive Check Power Consumption

The implementation of BoX-MAC-1 resulted in an astounding minimum receive check on-time of 0.78 ms, shown as the lighter trace in Figure 4. The majority of that time is spent in the process of powering the radio on and off, while only a few moments are dedicated to the actual CCA pin sampling. Each receive check consumes 32.26 uJ. As the power consumption comparisons in Figure 5 demonstrate, doubling the amount of receive checks per second does not significantly impact power consumption. We draw the conclusion that BoX-MAC-1's physical-layer receive checks consume so little power that the microcontroller and other peripherals quickly become dominating factors in power consumption.

Quiet gaps in modulation measured between packets within BoX-MAC-2's wake-up transmission were an average of 4.89 ms. These gaps can be accounted for by small CSMA backoffs, Rx / Tx switching, and SPI bus acquisition and control. The CSMA backoffs are randomized slightly which boosts the minimum BoX-MAC-2 energy-based receive check to 5.61 ms, not including oscillator startup. This BoX-MAC-2 receive check is depicted as the darker line in Figure 4. Compared to XMAC, BoX-MAC-2 results in a savings of 10 to 15 milliseconds per receive check which cuts receive check power consumption by 50% as compared in Figure 5. Each BoX-MAC-2 receive check consumes around 348.7 uJ of energy.

The evaluations of receive check performance also provided an opportunity to test the effects of an unintelligent Denial of Sleep attack against both BoX-MAC-1 and BMAC. BoX-MAC-2 and XMAC are not as interesting to evaluate against Denial of Sleep attacks because they inherently require layer 2 information to wake up entirely.

The attack was setup with receiver nodes performing periodic receive checks and the attacking node continuously modulating the channel using the CC2420's infinite transmission capabilities. Observations show the BoX-MAC-1 receiver wakes up temporarily for each receive check to listen for activity. After no packets are acquired, the BoX-MAC-1 receive simply returns to sleep. This behavior is far more desirable than that of BMAC, which stayed awake permanently until the attacker was removed from RF vicinity.

4.3. Network Power Consumption

A network with a high rate of traffic and a network with a low rate of traffic were tested to verify network power consumption. Emulating the network profiles of the models produced in Section 3.4, these tests consist of three transmitters sending unicast messages to a single receiver. This comparison allows us to compare deviations in results with the models in Figures 2 and 3. Sampled receive check intervals in both networks were defined separately to keep the test simple while accentuating behavior found mostly at the most extreme edges.

As expected, BoX-MAC-1 and BMAC prove to be inefficient for high traffic networks depicted in Figure 6. Transmissions dominate this high traffic network, causing layer 1 protocols to suffer. The cross-layer BoX-MAC-1 protocol outperforms the efficiency of BMAC by 13-24% simply due to the inclusion of both layer 2 information and extended backoffs. The cross-layer BoX-MAC-2 protocol is 10-25% more efficient than XMAC due to its layer 1 receive checks, and is 29-71% more efficient than BoX-MAC-1 as a result of its ability to end wake-up transmissions early.

Comparing the measurements of the high traffic network in Figure 6 with the high traffic network models in Figure 2,

we notice the relationships in efficiency between each protocol were predicted rather well. The actual inclusion of extended backoffs in BoX-MAC-1 prevent it from reaching BMAC's 100% radio on-time per day, which is one area where models underperform. Meanwhile, BoX-MAC-2 and XMAC seem to diverge in the actual results as opposed to the convergence depicted in the model of Figure 2. This, we believe, is a result of BoX-MAC-2's ability to nearly double throughput over XMAC, the effect of which is compounded for longer wake-up transmissions observed toward the right side of the plot. The actual layer 2 protocol results were much higher than predicted, simply because multiple packets are able to be delivered after a single receive check detection.

The low traffic network in Figure 7 demonstrates how the predominately layer 1 protocols are most efficient at higher volatilities. As the period between receive checks increases from left to right, the cross-layer BoX-MAC-1 protocol is up to 30% more efficient than BMAC due to the availability of layer 2 information. Layer 2 driven protocols become more efficient than their layer 1 counterparts as the duration of wake-up transmissions increase. At the longest receive check intervals and corresponding wake-up transmissions, BoX-MAC-2 exhibits 40% less energy consumption than XMAC.

Comparing the measured results of the low traffic network in Figure 7 with the calculated results in Figure 3, both point to a crossing point in efficiency around 300 ms. These measurements demonstrate that it is possible to use calculations to ascertain which BoX-MAC protocol may work best for a given network profile.

There are two main differences between the predicted and actual results of the low traffic network, however. First, BoX-MAC-1's predicted energy consumption from Figure 3 actually diverges away from BMAC which contradicts the measurements. One reason for this behavior is the exclusion of BoX-MAC-1's extended backoffs in calculation. As stated in Section 3.3, the omission of these extended backoffs in lower traffic networks may actually cause predicted energy consumption to fall short. Second, BoX-MAC-2 converges toward XMAC in the predicted results while it actually diverges in measurement. Again, we expect this is due to BoX-MAC-2's actual ability to nearly double throughput over XMAC, which is not accounted for analytically.

4.4. Network Throughput

A network consisting of one to nine transmitters sending unicast messages to a single receiver was developed to test how throughput is affected by various network parameters. Each transmitter in this network generates packets at a rate of one packet per second. By placing all nodes within RF vicinity, channel contention increases linearly with the number of transmitters.

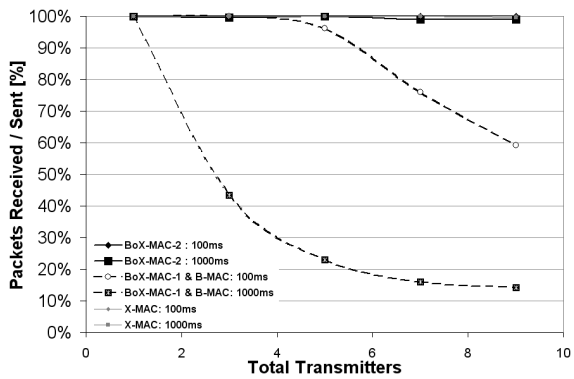

Figure 8. Network throughput versus traffic and channel contention with increasing transmitters.

Comparisons were made between BoX-MAC-1, BoX-MAC-2, and XMAC implementations with the receive check interval set at 100 and 1000 ms. These intervals were chosen because wake-up transmissions are proportional to receive check intervals, so we may observe the effects that wake-up transmissions on throughput. It is important to note there are no differences in throughput between the BoX-MAC-1 and BMAC implementations because transmission lengths cannot be decreased for any type of predominately layer 1 protocol. Consequently, BMAC is omitted from this analysis.

Figure 8 shows layer 1 based strategies exhibit a steep drop in performance as the number of transmissions increase on the channel. This reaffirms the argument that layer 1 strategies are not good choices for high transmission networks, especially in combination with fewer receive checks. The layer 2 based strategies perform at or near 100% throughput even in high density networks. This is because transmissions in these protocols are able to stop early and multiple packets can be delivered after a single receive check. A second throughput test was created to characterize the node-to-node maximum throughput for 10-byte packets. The receive check interval for this test was defined at 100 ms, keeping the corresponding wake-up transmissions rather short. As a consequence, layer 1 based wake-up transmissions must be at least 100 ms long, which greatly degrades their performance when compared to layer 2 based protocols.

Figure 9 renders the results of this maximum throughput test. The BoX-MAC-2 strategy is proven to have the highest throughput rate, which is approximately the maximum throughput we were able to achieve with the CC2420 set

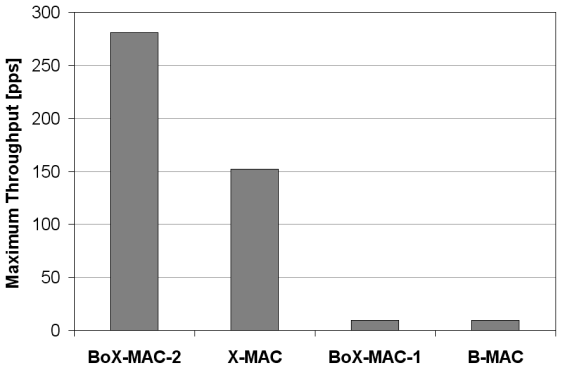

Figure 9. Maximum throughput for single node-to-node communications sending 10-byte packets.

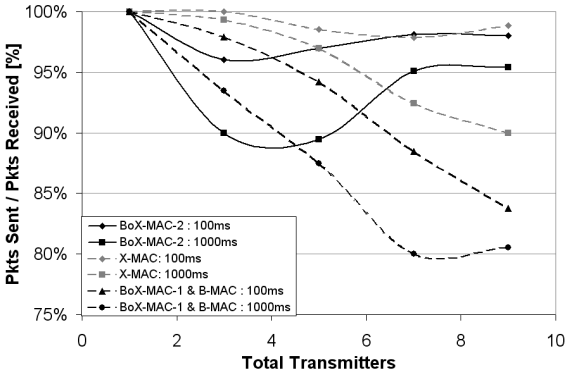

Figure 10. Reliability of packet deliveries versus increasing transmitters and channel contention.

at full power. The extra handshaking required by XMAC to receive the final payload is detrimental, and BoX-MAC-2 sees up to up to 46% more throughput than XMAC as a result. Finally, as predicted, layer 1 based strategies such as BoX-MAC-1 and BMAC have similar throughput characteristics that are very low due to their 100 ms per transmission condition set by the defined receive check interval. Adding logic to a BoX-MAC-1 transmitter allowing it to realize when a receiver is already awake will help it attain the maximum throughput of BoX-MAC-2.

4.5. Network Reliability

The reliability of packet deliveries naturally suffers as more transmitters contend for the channel. To test reliability we used a network of one to nine transmitters sending unicast messages every second to a single receiver. Again, as the number of transmitters within RF vicinity of each other increases, contention for the channel increases. The network receive check interval was set at 100 and 1000 ms to observe the effects of longer and shorter wake-up transmissions on reliability.

The most interesting characteristic of the results in Figure 10 is the non-monotonic behavior encountered by the BoX-MAC-2 strategy. We hypothesize this temporary performance hit is a result of radio on-time. As more transmitters are added and the number of transmissions increases on the channel, BoX-MAC-2 driven radios become active for longer periods of time which allows them to acquire more packets.

The reliability of mobile nodes quickly moving out of range was evaluated between BoX-MAC-1 and BMAC. BoX-MAC-2 and XMAC already incorporate layer 2 transmission strategies which largely mitigates the effects of mobility.

To characterize this behavior, a BoX-MAC-1 or BMAC mobile transmitter sends one-second long wake-up transmissions to a stationary low-power receiver. Turning off the transmitter node in the middle of its wake-up transmission definitively emulates moving it out of RF range.

This simple mobility test confirms that the layer 2 packetized wake-up transmission in BoX-MAC-1 will deliver its payload successfully, even before the end of its wake-up transmission. The BMAC implementation, however, is never able to deliver its final payload before moving out of RF range.

5. Future Work

There are four areas where standalone BoX-MAC protocols may be improved. First, a dynamic BoX-MAC protocol that automatically switches between BoX-MAC-1 and BoX-MAC-2 as network behavior and conditions change may significantly decrease power consumption without the need for input from a developer.

The second improvement to BoX-MAC protocols involves adding byte-level detections between energy checks and packet acquisitions. The CC2420 has access to byte-level information through its Start Frame Delimiter (SFD) pin [3]. If energy is detected on the channel but the SFD pin indicates the radio is not receiving bytes, the protocol may quickly turn the radio off. Conversely, if energy is detected and an extremely large frame is in the process of being received, the SFD line can help keep the radio on long enough to acquire that frame. This byte-level detection should be investigated to determine its effectiveness in decreasing network power consumption.

Third, improving BoX-MAC-1's transmission logic to

realize when it has recently communicated with a neighbor will prevent the transmitter from resending an unstoppable continuously packetized wake-up transmission. This will allow BoX-MAC-1 to attain the throughput efficiency of BoX-MAC-2.

Finally, variations of BoX-MAC protocols should be combined with synchronous protocols such as WiseMAC [14], SCP-MAC [21], or ZMAC [18] to examine how they may further improve energy efficiency in synchronous networks.

6. Conclusions

This paper explores the tension between simplistic single-layer and efficient cross-layer low-power protocols. Two novel low-power MAC protocols, BoX-MAC-1 and BoX-MAC-2, share a limited amount of cross-layer information to drastically improve performance of low-power networks over earlier BMAC and XMAC protocols. We emphasize that receive checks should be performed on the physical-layer while the decision to wake-up should be determined from link-layer information. It is demonstrated that BoX-MAC-1, which is a predominately layer 1 protocol utilizing link-layer continuously packetized wake-up transmissions, consumes up to 30% less energy than BMAC under reasonable workloads. BoX-MAC-2, a predominately layer 2 protocol that includes physical-layer receive checks, consumes up to 40-50% less energy than XMAC. Other effects of sharing cross-layer information include BoX-MAC-2's ability to increase througput by 46% over XMAC, and BoX-MAC-1's ability to support extended CSMA backoffs to reduce energy over BMAC during periods of channel contention. Furthermore, we confirm BoX-MAC-1 is able to support mobile nodes and circumvent Denial of Sleep attacks, which BMAC cannot.

The relative performance of BoX-MAC-1 and BoX-MAC-2 is quickly assessable through equations and models. High and low traffic network models were compared against actual networks implemented on CC2420-based platforms in TinyOS. These network profiles demonstrated the strengths and weaknesses of BoX-MAC-1 and BoX-MAC-2 against varying degrees of traffic and volatility, while actual measurements reaffirm predictions made through computational analysis.

In the future, dynamically selecting either BoX-MAC-1 or BoX-MAC-2 in the radio stack itself may help to automatically assume the most efficient BoX-MAC network deployment. These protocols may be combined with synchronous protocols to further increase efficiency and aid in the robustness of such implementations.

7. Acknowledgements

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