LA-MAC: Low-Latency Asynchronous MAC for Wireless Sensor Networks

Giorgio Corbellini*†, Emilio Calvanese Strinati*, and Andrzej Duda†
*CEA-LETI, MINATEC, Grenoble, France
†Grenoble Institute of Technology, CNRS Grenoble Informatics Laboratory UMR 5217, France
Email: [Giorgio.Corbellini, Emilio.Calvanese-Strinati]@cea.fr, Andrzej.Duda@imag.fr

***Abstract*—The paper presents LA-MAC, a low-latency asynchronous access method for efficient forwarding in wireless sensor networks. It is suitable for current and future sensor networks that increasingly provide support for multiple applications, handle heterogeneous traffic, and become organized according to some complex structure (tree, DAG, partial mesh). It takes advantage of the network structure so that a parent of some nodes becomes a coordinator that schedules transmissions in a localized region. Allowing burst transmissions improves the network capacity so that the network can handle load fluctuations. At the same time, the method reduces energy consumption by decreasing the overhead of node coordination per frame. The paper reports on the results of extensive simulations that compare LA-MAC with B-MAC and X-MAC, two representative methods based on preamble sampling. They show excellent performance of LA-MAC with respect to latency, delivery ratio, and consumed energy.**

I. Introduction

Much research effort has focused on developing MAC protocols that minimize energy consumption in wireless sensor networks [1]. The MAC access methods mostly aimed at wireless sensor networks supporting a single application that usually generated low traffic loads so that the communication channel was idle most of the time. The main design goal of access methods was minimizing energy consumption, which consists of reducing the effect of *idle listening* in which nodes consume energy waiting for an eventual transmission. Another energy consumption issue is related to *overhearing*, the reception of frames destined to other devices [1].

To save energy, devices aim at achieving low duty cycles: they alternate sleep periods (radio switched off) and active periods (radio switched on). As a result, the challenge of MAC design is to synchronize the instants of the receiver wake up with possible transmissions of nodes so that the network achieves a very low duty cycle.

The existing MAC methods basically use two approaches. The first one synchronizes devices on a common sleep/wake-up schedule by exchanging synchronization messages (SMAC [2], TMAC [3]) or defines a synchronized network wide TDMA structure (LMAC [4], D-MAC [5], TRAMA [6]). In the second approach, each node transmits a *preamble* before each data frame long enough to make sure that a potential receiver wakes up to get its frame (Aloha with Preamble Sampling [7], Cycled Receiver [8], LPL (Low Power Listening) in B-MAC [9], B-MAC+ [10], and CSMA-MPS [11] aka X-MAC [12], BOX-MAC [13], and DA-MAC [14]). Both approaches converge to the same scheme called *synchronous preamble sampling* that uses very short preambles and requires tight synchronization between devices (WiseMAC [15], Scheduled Channel Polling (SCP) [16]).

However, the domain of wireless sensor networks develops so quickly that the current and future networks present much different characteristics compared to their counterparts at the beginnings—we can mention the need for handling heterogeneous traffic, supporting multiple applications, dealing with more complex network structures, and providing seamless self-organization. To take into account such new requirements, we propose LA-MAC, a low-latency asynchronous access method for efficient forwarding in wireless sensor networks. Its operation is the following:

- Neighbor nodes are organized in a structure corresponding to the routing information (a tree, a DAG, a Clustered Tree, or a mesh). In particular, a node knows its parent (a next-hop node) on a given route.
- Potential receiver nodes (parents) periodically wake up each *check interval* and wait for the reception of a series of short preambles. Nodes can adapt their check intervals to handle variations of traffic.
- Nodes contend for a transmission of a *burst* to the next-hop by sending a series of short preambles with the information that allows the next-hop to schedule transmission bursts based on priority, age of a burst, burst size. Grouping packet transmission allows to handle higher volumes of data closer to a sink and limits energy consumption by reducing the protocol overhead.
- The next-hop allocates the channel to transmitters by sending an ACK frame that defines rendezvous later on for transmitting a burst of frames. Nodes can schedule earlier transmissions of high priority traffic.
- A transmitter node goes to sleep, wakes up at the instant of a given rendezvous, performs a CCA (Clear Channel Assessment), and sends its burst.

We report on extensive simulations of our method comparing to two other representative protocols based on preamble sampling: X-MAC and B-MAC. We have defined several scenarios to validate the behavior of the proposed MAC in a realistic radio environment. Our simulation results show excellent performance of the proposed MAC compared to X-MAC and B-MAC.

II. LA-MAC Protocol

The motivation for the design of LA-MAC protocol comes from the fact that no existing MAC access method can efficiently adapt its behavior (time of reaction, energy consumption, and latency) to the variation of some network parameters such as traffic fluctuations. The requirements for LA-MAC are the following:

Heterogeneous traffic. The first MAC methods focused on energy savings when two nodes needed to send sporadic periodic measurements. Current networks may include nodes with various characteristics (different computational power, type of power supply, mobility capabilities) that generate other types of traffic: sporadic alarms, periodic high-volume multimedia data (images or video), real-time control commands for actuators [17], [18]. Moreover, when networks are large and dense, nodes close to sinks may need to transport increasingly high volumes of data with some QoS constraints, e.g. low latency. As the performance of batteries improves and alternative energy scavenging technologies appear, the criticality of taking into account energy savings in the network operation becomes less stringent. Nevertheless, optimizing energy consumption is still important, but at the same time, it is also important to take into account performance aspects such as higher throughput, lower latency, and provision for traffic differentiation. Moreover, variations in traffic call for adaptation mechanisms that adjust the operation to a given load. The last aspect concerns unicast vs. broadcast communications—convergecast traffic towards sinks is the most important, however self-organizing operation also requires some support for broadcast communications that may become a problem when neighbor nodes use different channels or wake up instants.

Support for multiple applications. First wireless sensor networks were typically designed for a specific application that generated one type of low intensity traffic [19], [20]. Current wireless sensor networks become multi-purpose and can convey heterogeneous traffic coming from different applications [21]. This trend benefits from the IETF ROLL (Routing Over Low power and Lossy networks) standardization effort that fosters the development of more generic wireless sensor networks connected to the Internet following the way similar to the early Internet with a common communication infrastructure independent of applications.

More Complex Network Structure. At the beginning, wireless sensor networks had a simple tree structure reflecting the need for transporting measured data to a single sink. This situation is changing with multiple coexisting applications, possible multiple sinks and even mobile nodes or sinks. RPL (Routing Protocol for Low Power and Lossy Networks) [22] defines the structure of a DAG (Directed Acyclic Graph) for Multi-Point-to-Point traffic (MP2P - routing packets to a single sink) and considers multiple sinks with parallel DAGs. It begins to take into account the need for Point-to-Point traffic (P2P), which finally will result in a design of a full-fledged routing protocol between any pair of sources and destinations. A MAC protocol needs to take into account the role of a node in a given structure and contribute to efficient forwarding with mechanisms like staggering transmission instants for forwarding in a tree defined by D-MAC [5].

Self-organization. Small scale and single application networks could make do with manual deployment and configuration. For instance, Wavenis nodes are manually inserted in a tree rooted at the sink and their virtual channels (frequency hopping sequence and time offset) are configured by an operator [23]. Large-scale networks require a self-organizing operation in which a node discovers its neighbors and integrates itself within a given structure.

So, our goal is to design an adaptive MAC protocol suitable for large-scale multi-purpose heterogeneous wireless sensor networks running a routing protocol that structures their operation. We want to take into account different types of traffic by providing support for service differentiation and support efficient multi-hop packet forwarding by making MAC to operate according to the network structure and possible multiple routes established at the network layer.

Most of existing MAC protocols that address such objectives rely on network-wide synchronization (D-MAC [5], Q-MAC [24], BurstMAC [25], PR-MAC [26], QOS-MAC [27]). The characteristics of the new kind of wireless sensor networks made us consider the approach based on asynchronous *preamble sampling* instead of synchronized methods, because achieving time synchronization on a large scale and in networks with dynamic topology is difficult. Moreover, synchronization implies some overhead that is cumbersome in case of traffic variations. With the choice of the asynchronous approach, we can deal with scalability, because close cooperation of nodes required by efficient forwarding will be localized to small groups of nodes. Such an approach can also cope with evolving network topology and node mobility (however this last aspect is not considered in the present paper, which is a subject of an on-going work).

LA-MAC tries to achieve its objectives by building on three main ideas: efficient forwarding based on proper scheduling of children nodes that want to transmit, transmissions of frame bursts, and traffic differentiation. The method periodically adapts the organization of channel access depending on network dynamics. If more nodes are active at the same time, it acts so that all of them can transmit without collisions.

Fig. 1 illustrates the operation of the LA-MAC protocol for monitoring traffic: there are two transmitters with bursts of data frames to forward to the same destination. LA-MAC consists of several consecutive steps.

Step 1: Wake-up and sense the channel

Devices periodically alternate long sleep periods with short Channel Sensing (CS) intervals. CS duration is the same for all devices, however devices are not synchronized so they wake-up and sensing may start at different instants. In the example, we assume that both devices have some frames to send and that both devices are able to decode all frames (each device is within the transmission range of the other). Transmitter 1

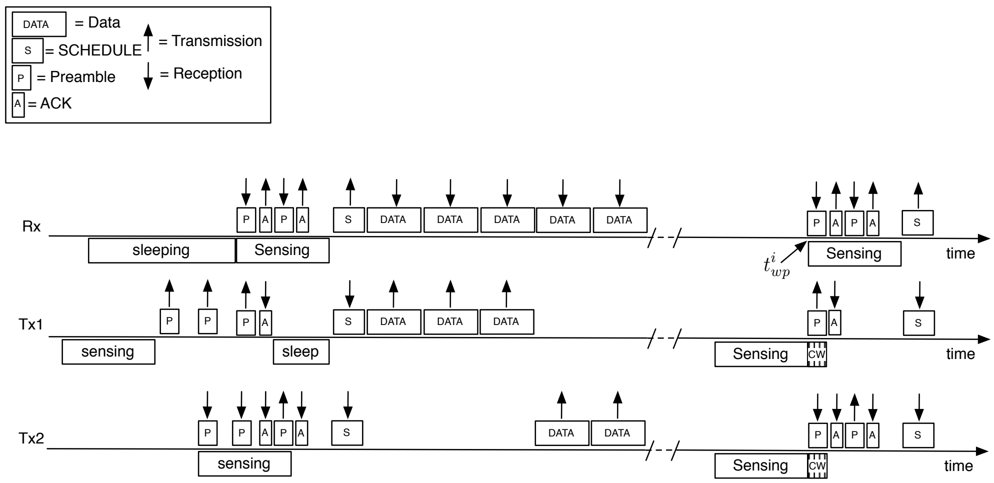

Figure 1. LA-MAC operation during the transmission of two bursts of frames

(Tx1 in the figure) is the first device to wake up, it turns its radio into the idle mode, and starts its channel sensing CCA procedure.

Step 2: Preamble sampling

When the CCA ends and the channel is clear, Tx1 starts sending a sequence of short preambles containing the information about the burst to send. As illustrated in the figure, the first preamble is not received by any of other devices, because they are in the sleep mode. Tx2 receives the second preamble and although it is not the intended receiver of this frame, it interprets the preamble as a blocking signal so it remains silent until the reception of the parent ACK, it then can start transmitting its own preambles.

A short preamble conveys some information about the status and the size of its local packet queue: *Destination*, *Priority of the burst*, *Age of the burst*, and *Burst size*.

Overhearing preambles reduces interference between neighbor devices. However, it may happen that a device overhears a preamble, but not its corresponding ACK. To avoid deadlock, devices use a timeout equal to the channel sensing period.

Step 3: Preamble clearing with a rendezvous

When the intended destination (Rx in the figure) receives and correctly decodes a preamble (no collision occurs), it immediately "clears" it by sending back an ACK frame containing the instant of a *rendezvous* at which Rx will broadcast a SCHEDULE frame with the result of its scheduling decision. An ACK also forces a sender to stop transmitting short preambles so that another one can transmit its preamble with success. After receiving an ACK, a sender goes to sleep and it wakes up at the instant of the rendezvous. In the figure, after the transmission of an ACK to Tx1, the Rx device is again ready for receiving preambles from other devices. So, Tx2 transmits a preamble and receives an ACK with the same rendezvous. Preamble-clearing continues until the end of the channel sensing interval of the receiver.

Step 4: Broadcast of the SCHEDULE frame

The Rx device processes burst requests according to the priority first, then if multiple devices have frames of the same priority, according to the age of frames waiting for transmission, and otherwise, all children devices equally share channel access. Senders are scheduled until there is room for transmissions, that is, each receiver, allocates transmission of data for an overall duration equivalent to the time remaining until its next wake up time. At the end of CS, Rx broadcasts the SCHEDULE frame that contains a list of instants at which transmitters can transmit their bursts.

Step 5: Burst transmission

After receiving the SCHEDULE frame, senders transmit their bursts at the defined instants. While waiting for its turn, a sender can go to sleep and wake up at the instant of its transmission.

Step 6: Data forwarding

If the received data frame contains a packet to forward to one of the sinks, Rx will take the role of the sender device and start sending its short preambles, immediately if the wake-up schedule of Rx is unknown, or at a specific time instant otherwise.

Moreover, Rx devices in the hierarchy may have sensing periods delayed by some offsets that allow for forwarding packet operation like in D-MAC, however devices do not need to be precisely synchronized.

Step 7: Next wake-up period

To adapt the wake-up schedule of senders with respect to the schedule of receivers, each sender needs to know two elements: the next wake up instant of the Rx device (t^i_{wp}) and the estimated number of contending senders (C^i). t^i_{wp} is contained inside each ACK frame together with the rendezvous instant while the estimation of the number of senders is sent in the SCHEDULE frame, because to estimate the number of its senders Rx needs to gather as much preambles as possible.

Based on this information, each sender can adapt its wake-up schedule: sender j will start its CCA at $t^i_{wp} - D^j_{cs}$, where t^i_{wp} is the wake-up instant of Rx device i and D^j_{cs} is the duration of the channel sensing of device j. To avoid collisions of preambles sent by several senders at this instant, if a sender detects a transmission of a preamble frame, it will randomly choose a slot within a contention window of CW (whose size depends on C^i) according to a uniform distribution.

Transmission of Broadcasts. If a device needs to broadcast a burst of frames, it marks the burst as broadcast in the preamble and also specifies a *broadcast rendezvous*. All devices that receive the broadcast preamble check the value of the *broadcast rendezvous* field, go to sleep, and wake up at the *rendezvous* for broadcast reception.

III. Simulation Results

A. Simulation assumptions

We consider several sensor networks composed by *N* devices and *S* sinks. Devices can generate several different traffic classes $Tr_i \forall i \in (1, C)$, each class with priority Pr_i.

All simulations consist of two phases: during the first, the network is flooded with ETX probes [28] and routes toward the sinks are built according to RPL (Routing Protocol for Low power and Lossy Networks) [22] to structure the topology as a DODAG (Destination Oriented Directed Acyclic Graph). Both ETX probes and RPL route discovery messages are broadcast. During the first phase no application layer messages are generated. In the second phase, nodes generate application layer traffic. To simplify presentation without reducing generality, we consider in the rest of this paper two classes of application layer traffic: time-driven periodic traffic, and sporadic event-driven bursty *alarm* traffic with possible high variable intensity. The periodic traffic is unicast. Unicast messages, also called *Monitoring*, mimic sources like traffic light reporting about the traffic intensity or houses/apartment blocks reporting about the current energy consumption. All devices except the sinks periodically generate monitoring messages with rate r_m packets-per-second (pps). The sinks only generates broadcast messages to build and maintain RPL routes. The alarm traffic is sporadic and composed by bursts of b alarm messages generated by *A* devices.

At the end of the first phase, each device has several *rank* values that are its distances to a given sink in terms of the number of hops.

We consider two simulation scenarios for WSNs. In the first one, devices form a grid topology and communication is multi-hop with multiple traffic types. In the second one, we investigate the hidden terminal problem with high traffic load.

In terms of timing constraints, monitoring packets do not have latency constraints while alarm packets must reach one of the sinks as soon as possible.

Performance criteria are the following:

Latency [s]: the average delay between the instant of packet generation and the instant of packet reception at the sink.

Energy Consumption:[Joules]: the energy consumed by a node due to radio activity.

Delivery Ratio [%]: the ratio of the number of received packet by the sink to the total number of generated packets.

Packet Drop Ratio [%]: the ratio of the number of packets that must be discarded by MAC layer due to unlimited buffer size..

B. Numerical Results

We have evaluated the LA-MAC protocol using the open source simulator OMNeT++ [29]. Moreover, we assume that devices use the CC1100 [30] radio stack with bitrate of 20K bps. The values of power consumption for different radio modes are specific to the CC1100 transceiver considering a 3 V battery.

We present simulation results for the case of a single sink. We compare the LA-MAC performance with two MAC protocols: B-MAC with a Contention Window [9], [16] and X-MAC [12]. We have chosen B-MAC with Contention Window, because it is does not require device synchronization and X-MAC, because it is energy efficient and can adjust protocol parameters to take into account changing network conditions.

Simulation results are averaged over 10 runs and we compute 95 % confidence intervals. During a given simulation run traffic generation rate r_m is the same for all devices, but they generate packets at some random instants. Each device generate 10000 application messages, so that if a device generated all messages before the end of the simulation, it continues to behave as a relay node. The parameters for LA-MAC are the following: channel sensing interval $CS = 25ms$, interval between two *CS* of $250\ ms$. The contention window of B-MAC is 32 slots. B-MAC and X-MAC have the same wake-up up period of $250\ ms$. Data frames are transmitted only once, that is, there are no re-transmissions. Data buffers at MAC layer have a limited size equal to 50 messages.

C. Scenario 1: Heterogeneous Traffic

In this scenario, communication is multi-hop and devices can act as sensors as well as relays. During each simulation run of 100000 s, r_m varies within a very large range $r_m \in [0.002, .., 0.1]\ pps$. In our network setting, $N = 100$ nodes are deployed in a grid of 10x10 with the sink located in one of the corners to create a network with a very large number of hops (the farthest device from the sink has rank 18). All devices generate periodical monitoring packets except one node (that is, $A = 1$) that generates both monitoring and bursts of alarm frames. The size of burst of alarm messages is $b = 20$. We present the results for the case in which the alarm generator has the rank equal to 10. From Fig. 2 we can observe that LA-MAC permits to deliver almost all messages (alarms and monitoring) to the sink. As traffic load increases, both X-MAC and B-MAC suffer from increased traffic congestion and most of the messages collide. We do not consider re-transmissions, so if a packet collide because of high congestion, it is lost. With increased network congestion one would expect the average latency to explode, however, the results that we provide concern the case without re-transmissions, which explains the fact that latency slightly increases with traffic load (cf. Fig. 3).

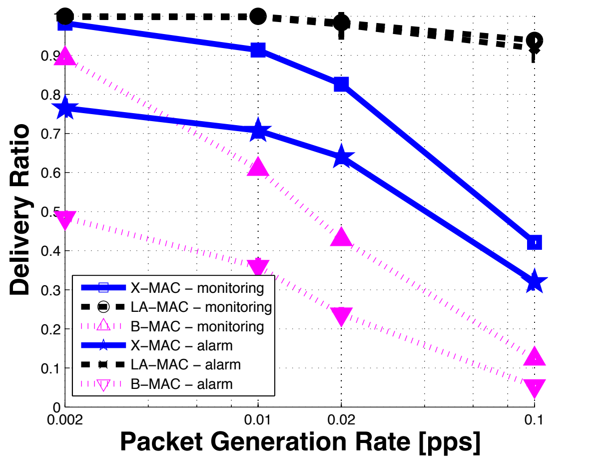

Figure 2. Scenario 1: Delivery ratio of alarm and monitoring frames vs. packet generation rate. 100 nodes are deployed in a 10x10 grid, alarm source has rank 10.

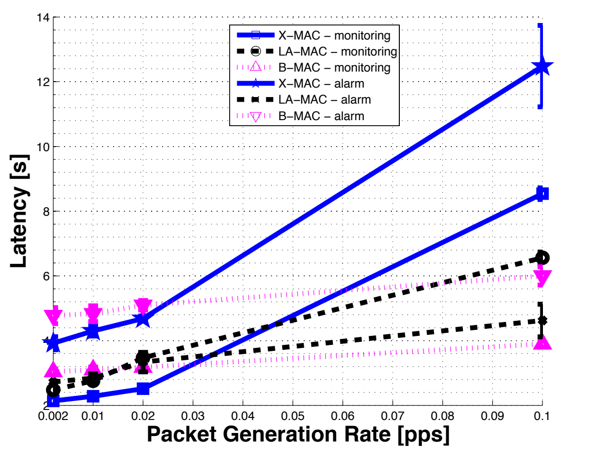

Figure 3. Scenario 1: Latency of alarm and monitoring frames vs. packet generation rate. 100 nodes are deployed in a 10x10 grid, alarm source has rank 10.

The Average latency obtained with LA-MAC gradually grows with traffic load. Even though the number of delivered messages increases, LA-MAC is able to handle high congestion. Neither B-MAC nor X-MAC are able to differentiate traffic priority, thus, packets are served at the FIFO order in the MAC buffer. As a result, sporadic alarms are penalized as they come in bursts of 20 messages. When traffic load is very high, we observe that B-MAC provides lower latency that LA-MAC for monitoring messages, however, this value must be weighted by the delivery ratio for this particular traffic congestion (12.3 % for B-MAC against 93.5% for LA-MAC). The reason for the high latency of X-MAC, is that the protocol is not able to support such high traffic load. With heavy traffic load in fact, nodes spend long time sending preambles to wake-up their next hop because most of the preambles collide, as a result, data messages wait very long time in the MAC buffer before being sent to the receiver. In this scenario, any message is dropped at the MAC layer because of the limited buffer size.

We show in Fig. 4 the average energy consumption per node at the end of simulation. Although LA-MAC provides high delivery ratio and low latency, it results in the less energy consuming protocol. Energy consumption includes the energy spent by each node for building and maintaining routes.

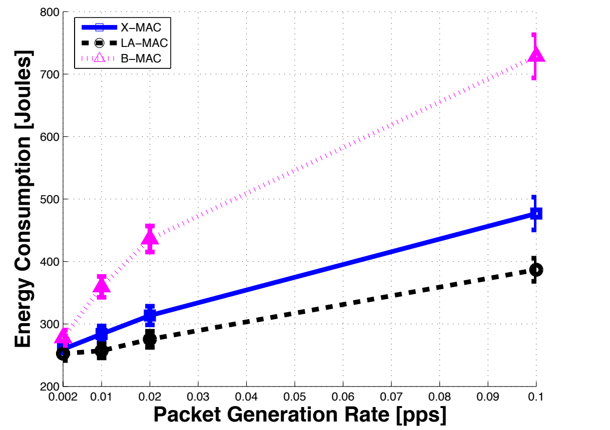

Figure 4. Scenario 1: Energy consumption vs. packet generation rate. 100 nodes are deployed in a 10x10 grid, alarm source has rank 10.

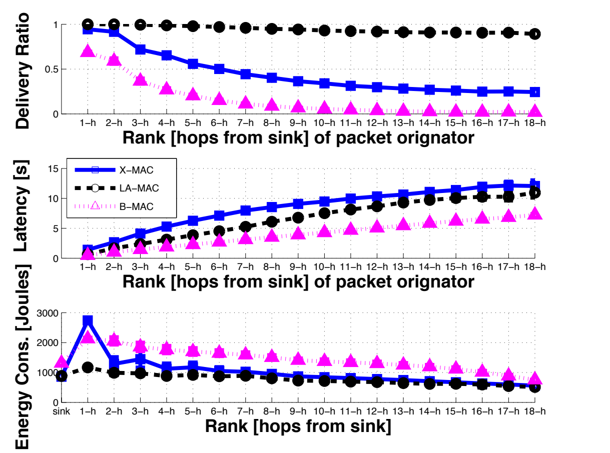

Figure 5. Scenario 1: Performance vs. the rank of nodes. 100 nodes are deployed in a 10x10 grid, alarm source has rank 10. High traffic load case, that is, PPS=0.1.

Thanks to the ability of burst forwarding and traffic differentiation, LA-MAC is also able to guarantee high delivery ratio for devices that are very far from the sink. In Fig. 5, we show the delivery ratio of monitoring messages, the average latency, and the energy consumption with respect to the rank of the message generator for the case of high traffic load, that is, $r_m = 0.1pps$. We observe again that B-MAC is able to deliver monitor messages with low latency (cf. Fig. 3), however, the number of delivered messages is almost zero for nodes that are far from the sink. As expected, the nodes that are far from the sink consume less energy, which is the result of convergecast traffic that causes higher congestion and consumption in the region around the sink.

D. Scenario 2: Hidden Terminal

In this scenario, two senders (hidden from each other), transmit data to the sink. During each simulation run of $10000\ s$, r_m varies within a range $r_m \in [1,..,20]\ pps$, that results in a very high traffic load. In this scenario, only one of the transmitters can generate alarms (that is, $A = 1$). The reason for such traffic generation rate range is that we want to analyze the hidden terminal problem with medium-to-high congestion conditions. High congestion with hidden transmitters mimics the operation that occurs in the region of the sink in a large network such as the one represented in scenario 1. In fact, in a large multi-hop WSN with convergecast traffic, even though the traffic generation rate is low, the number of packets that must be handled by the nodes around the sink is very high, which results in high energy consumption. This phenomenon is called the *funneling effect* and it can be observed in Fig. 5.

We can observe in Fig. 6 that LA-MAC is robust with respect to the hidden terminal problem, *i.e.*, it is able to deliver almost all messages. X-MAC and B-MAC suffer from the hidden terminal problem, instead. When traffic load is low, that is $r_m = 1\,pps$, the channel is clear most of the time and only B-MAC is not able to deliver all messages because of the collision of long preambles and data messages. As traffic load increases, the probability for each transmitter to have a packet to send each time it wakes up increases as well. In the case, if $r_m = 10\,pps$, each transmitter has an average of 2.5 messages to send, thus both transmitters try to wake up the sink with preambles all the time they wake up. The result is a very busy channel with many preambles that collide at the sink. In X-MAC, when a node sending a preamble receives an ACK coming from its parent destined to another device, it initializes a timer with a random back-off time and directly transmits its data message when the timer expires. This mechanism is a sort of a traffic load adaptation and allows the transmission of two messages per wake-up period instead of only one in B-MAC. For this reason, the sink remains awaken after the end of data reception for an extra time to receive another possibly incoming packet. Even though the random back-off time is long enough to permit the first transmission to finish, if both hidden terminals have a message to send and choose a random back-off before directly transmitting their messages, data frames may collide. This is the reason for the low delivery ratio of X-MAC starting from traffic load of $r_m = 10\ pps$. Moreover, when traffic load becomes high and the network is saturated the percentage of dropped packets increases (cf. Tab. I).

Fig. 7 shows the results for latency vs. increasing traffic load. As observed in the results of scenario 1, LA-MAC delivers messages with lower latency. The reason for the floor of latency observed in B-MAC and X-MAC is the limited buffer size—starting from $r_m = 10\,pps$ the network is saturated and all messages are delivered with the same latency.

Fig. 8 shows the percentage of time nodes spend in each radio mode. We observe that in the case of very high traffic load, the percentage of time nodes spend in the sleep state

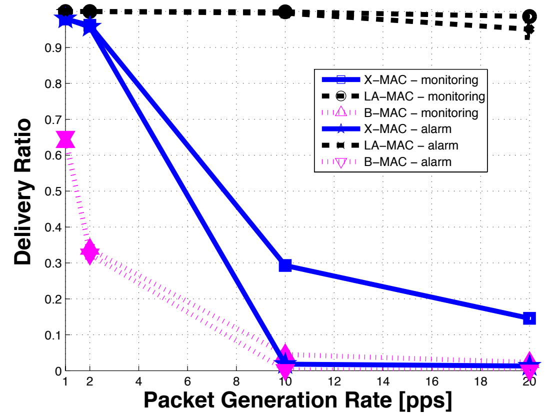

Figure 6. Scenario 2: Delivery ratio vs. packet generation rate.

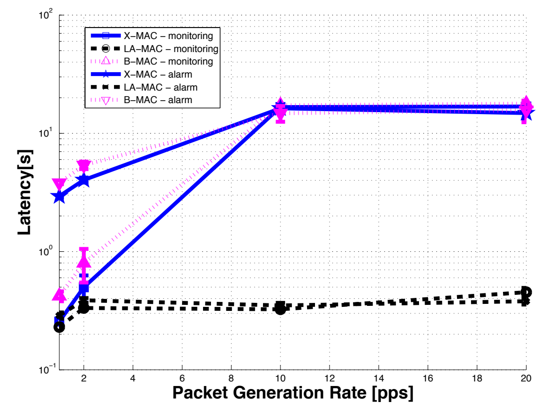

Figure 7. Scenario 2: Latency vs. packet generation rate.

increases, because when traffic load is very high such as in the case of $r_m = 20\,pps$, nodes generate all their application messages very quickly and then they only periodically poll the channel and sleep until the end of simulation.

Protocol \ r_m	1 pps	2 pps	10 pps	20 pps
X-MAC pps	0 %	0.015%	46.55 %	56.48 %
B-MAC pps	0 %	0.047 %	47.60 %	57.05 %
LA-MAC pps	0 %	0 %	0.059 %	0.98 %

Table I
SCENARIO 2: PACKET DROP DUE TO THE LIMITED BUFFER SIZE VS. PACKET GENERATION RATE.

IV. CONCLUSIONS

The motivation for the work presented in this paper comes from the observation that existing MAC access methods are not longer suitable for current and future sensor networks that increasingly provide support for multiple applications, handle heterogeneous traffic, and become organized according to some complex structure (tree, DAG, partial mesh). We also observe that relying on synchronized methods is no longer possible, because of the network scale and dynamic evolution. The paper thus proposes LA-MAC, a low-latency asynchronous access method for efficient forwarding in wireless sensor networks.

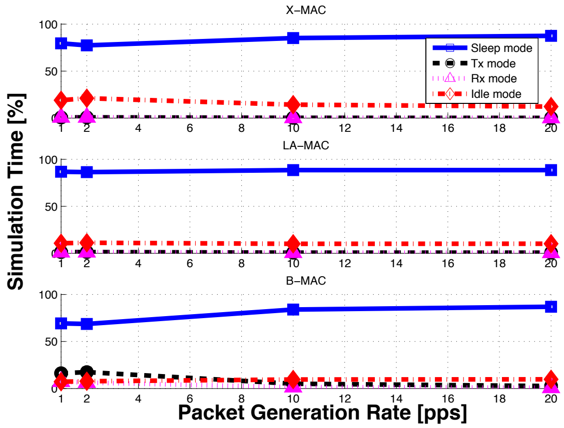

Figure 8. Scenario 2: Percentage of time spent in each radio mode vs. packet generation rate.

We report on the results of extensive simulations that compare LA-MAC with B-MAC and X-MAC, two representative methods based on preamble sampling. We include the results for two important spatial scenarios that show excellent performance of LA-MAC with respect to latency, delivery ratio, and consumed energy. Other not reported scenarios also confirm the superiority of the proposed scheme.

We continue to investigate LA-MAC and its ability to handle mobile nodes. One of the reasons for choosing an asynchronous preamble sampling based method was the need for taking into account mobility. We plan to analyze the performance of LA-MAC in a sensor network with mobile nodes and sinks through simulation and compare the results with other proposed methods for mobile nodes.

Acknowledgments

A part of this work has been performed in the framework of the ICT project ICT-5-258512 EXALTED partly funded by the European Commission. The author Calvanese Strinati would like to acknowledge the contributions of their colleagues from the EXALTED project, although the expressed views are those of the authors and do not necessarily represent the project. This work was also partially supported by the European Commission project CALIPSO under contract 288879, the French National Research Agency (ANR) projects ARESA2 under contract ANR-09-VERS-017, and IRIS ANR-11-INFR-016.

References

[1] K. Langendoen, "Energy-Efficient Medium Access Control," *Book chapter in Medium Access Control in Wireless Networks, H. Wu and Y. Pan (editors), Nova Science Publishers*, 2008.

[2] W. Ye, J. Heidemann, and D. Estrin, "An Energy-Efficient MAC Protocol for Wireless Sensor Networks," *IEEE Infocom*, pp. 1567–76, New York, NY, July 2002.

[3] T. van Dam and K. Langendoen, "An Adaptive Energy-Efficient MAC Protocol for Wireless Sensor Networks," *In Proc. of ACM Sensys*, pp. 171–80, Los Angeles, CA, November 2003.

[4] L. van Hoesel, P. Havinga, "A lightweight medium access protocol (LMAC) for wireless sensor networks: Reducing Preamble Transmissions and Transceiver State Switches," *In Proc. of INSS*, Tokyo, Japan 2004.

[5] G. Lu, B. Krishnamachari, and C. Raghavendra, "An adaptive energy-efficient and low-latency MAC for data gathering in wireless sensor networks," in *IEEE IPDPS*, 2004, p. 224.

[6] V. Rajendran, J. J. Garcia-Luna-Aceves, and K. Obraczka, "Energy-Efficient, Application-Aware Medium Access for Sensor Networks," *IEEE MASS*, 2005.

[7] A. El-Hoiydi, "Aloha with Preamble Sampling for Sporadic Traffic in Ad Hoc Wireless Sensor Networks," *IEEE ICC*, New York, NY, USA, April 2002.

[8] E-Y. Lin, J. Rabaey, A. Wolisz, "Power-Efficient Rendez-vous Schemes for Dense Wireless Sensor Networks," *IEEE ICC*, Paris, France, June 2004.

[9] J. Polastre, J. Hill and D. Culler, "Versatile Low Power Media Access for Wireless Sensor Networks," *ACM SenSys*, 2004.

[10] M. Avvenuti, P. Corsini, P. Masci, and A. Vecchio, "Increasing the efficiency of preamble sampling protocols for wireless sensor networks," in *IEEE MCWC*, 2006, pp. 117–122.

[11] S. Mahlknecht and M. Boeck, "CSMA-MPS: A Minimum Preamble Sampling MAC Protocol for Low Power Wireless Sensor Networks," *IEEE WFCS*, Vienna, Austria, September 2004.

[12] M. Buettner et al., "X-MAC: A Short Preamble MAC Protocol For Duty-Cycled Wireless Networks," *ACM SenSys*, Boulder, CO, November 2006.

[13] R. Kuntz, A. Gallais, and T. Noel, "Auto-adaptive mac for energy-efficient burst transmissions in wireless sensor networks," in *IEEE WCNC*. IEEE, pp. 233–238.

[14] G. Corbellini, E. Calvanese Strinati, E. Ben Hamida, and A. Duda, "DA-MAC: Density Aware MAC for Dynamic Wireless Sensor Networks," in *IEEE PIMRC*, September 2011.

[15] C. Enz, A. El-Hoiydi, J. Decotignie, V. Peiris., "WiseNET: An Ultralow-Power Wireless Sensor Network Solution," *IEEE Computer*, vol. 37, no. 8, pp. 62–70, August 2004.

[16] W. Ye, F. Silva and J. Heidemann, "Ultra-Low Duty Cycle MAC with Scheduled Channel Polling," *ACM SenSys*, Boulder, CO, USA, November 2006.

[17] M. Yarvis, N. Kushalnagar, H. Singh, A. Rangarajan, Y. Liu, and S. Singh, "Exploiting heterogeneity in sensor networks," in *IEEE Infocom*, vol. 2, 2005, pp. 878–890 vol. 2.

[18] X. Du, Y. Xiao, and F. Dai, "Increasing network lifetime by balancing node energy consumption in heterogeneous sensor networks: Research articles," *Wirel. Commun. Mob. Comput.*, vol. 8, no. 1, pp. 125–136, 2008.

[19] P. Juang, H. Oki, Y. Wang, M. Martonosi, L. S. Peh, and D. Rubenstein, "Energy-efficient computing for wildlife tracking: design tradeoffs and early experiences with ZebraNet," *SIGOPS Oper. Syst. Rev.*, vol. 36, no. 5, pp. 96–107, 2002.

[20] "ARGO - Global Ocean Sensor Network." [Online]. Available: http://www.argo.ucsd.edu

[21] J. Steffan, L. Fiege, M. Cilia, and A. Buchmann, "Towards Multi-Purpose Wireless Sensor Networks," in *IEEE SENET*, August 2005.

[22] The ROLL Design Team, "RPL: Routing Protocol for Low Power and Lossy Networks," https://datatracker.ietf.org/doc/draft-ietf-roll-rpl/, March 2011.

[23] "http://www.wavenis-osa.org."

[24] Y. Liu, I. Elhanany, and H. Qi, "An Energy-Efficient QoS-Aware Media Access Control Protocol for Wireless Sensor Networks," in *IEEE MASS*, 2005.

[25] M. Ringwald and K. Römer, "BurstMAC: an Efficient MAC Protocol for Correlated Traffic Bursts," in *IEEE INSS*, 2009, pp. 1–9.

[26] H. Kim and S.-G. Min, "Priority-based QoS MAC Protocol for Wireless Sensor Networks," in *IEEE IPDPS*, 2009, pp. 1–8.

[27] K.-J. Paek, J. Kim, U.-S. Song, and C.-S. Hwang, "Priority-Based Medium Access Control Protocol for Providing QoS in Wireless Sensor Networks," *IEICE - Trans. Inf. Syst.*, vol. E90-D, no. 9, pp. 1448–1451, 2007.

[28] D. De Couto, "High-Throughput Routing for Multi-Hop Wireless Networks," Ph.D. dissertation, 2004. [Online]. Available: http://pdos.csail.mit.edu/papers/grid:decouto-phd/thesis.pdf

[29] "OMNeT++ Discrete Event Simulator." [Online]. Available: http://www.omnetpp.org.

[30] "Texas Instruments, CC1100 datasheet." [Online]. Available: http://focus.ti.com/docs/prod/folders/print/cc1100.html.