MAC Protocol Engine for Sensor Networks

Sinem Coleri Ergen, Piergiuseppe Di Marco, Carlo Fischione

Abstract—**We present a novel approach for Medium Access Control (MAC) protocol design based on protocol engine. Current way of designing MAC protocols for a specific application is based on two steps: First the application specifications (such as network topology and packet generation rate), the requirements for energy consumption, delay and reliability, and the resource constraints from the underlying physical layer (such as energy consumption and data rate) are specified, and then the protocol that satisfies all these constraints is designed. Main drawback of this procedure is that we have to restart the design process for each possible application, which may be a waste of time and efforts. The goal of a MAC protocol engine is to provide a library of protocols together with their analysis such that for each new application the optimal protocol is chosen automatically among its library with optimal parameters. We illustrate the MAC engine idea by including an original analysis of IEEE 802.15.4 unslotted random access and Time Division Multiple Access (TDMA) protocols, and implementing these protocols in the software framework called SPINE, which runs on top of TinyOS and is designed for health care applications. Then we validate the analysis and demonstrate how the protocol engine chooses the optimal protocol under different application scenarios via an experimental implementation.**

Index Terms—**Wireless Sensor Networks, IEEE 802.15.4, Medium Access Control Protocols.**

I. Introduction

Wireless sensor networks (WSNs) consist of a group of nodes, each comprising one or more sensors, a processor, a radio and a battery. Their operations must be energy efficient, because the energy supply of the battery is often limited. Moreover, WSNs are called to offer packet transmission with adequate delay and reception rates for many applications, such as health care, traffic monitoring, active vehicle control systems, and environmental monitoring. Each of these applications requires high performance in its own domain with a different set of requirements for energy consumption, delay and reliability (packet reception rate), different network characteristics (network topology and data generation), and different underlying physical layer technology. The need for the rapid design of protocols for such a variety of application domains brings up the challenge of understanding performance of protocols in various application-specific contexts and automating the protocol design for each new application.

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Piergiuseppe Di Marco and Carlo Fischione acknowledge the support the Swedish Foundation for Strategic Research, the Swedish Research Council, the Swedish Governmental Agency for Innovation System, and EU integrated project FeedNetBack.

In a WSN energy consumption depends on several factors. Nodes measure local physical parameters and send raw or interpreted data to a data collection center. The amount of data to be sent and the arrangement of nodes with respect to the data collection center together with the communication environment depends on the requests of the application. Moreover, the network as a whole has to meet certain lifetime, delay and reliability constraints. Since the sensor nodes in the network may not be recharged once their energy is drained, their lifetime is determined by the application. Many applications, e.g. security monitoring, require guaranteed arrival of sensor data to the collection center and others require a certain degree of reliability in delivering sensor data (e.g., control and automation applications). The underlying physical layer technology on the other hand determines the resource constraints such as the energy spent in communication states such as receive, transmit and sleep, and physical layer data rate.

The network's medium access control (MAC) protocol, which determines how the radios are operated, has a decisive influence in identifying whether the application requirements can be satisfied. Current way of designing a MAC protocol for a specific application is first to identify the application specifications such as network topology and packet generation rate, the application requirements for energy consumption, delay and reliability, and the resource constraints from the underlying physical layer such as energy consumption and data rate and then design the protocol that satisfies all these constraints, e.g. MAC protocol design for traffic monitoring application [1] and MAC protocol design for Intelligent Tire application [2]. The performance of the protocol is usually demonstrated via simulations for the specific applications. The main drawback of this procedure is that we have to restart the design process for each possible application, which may be a waste of time and effort.

This paper proposes a novel MAC protocol design approach based on MAC protocol engine as depicted in Figure 1. MAC protocol engine contains a library of protocols. The idea is to provide the analysis of each protocol in the engine such that it chooses the optimal protocol among its library with optimal parameters for the specific topology, packet generation rate taking into account the corresponding physical layer technology and hardware for data rate and energy consumption satisfying constraints for energy, delay and reliability. This design technique requires also changing the existing approach to protocol design. Currently, when a protocol is designed, performance is usually illustrated through simulations only and often lack a formalization

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of the protocol that would provide the necessary insights for optimal implementation in different scenarios [3]. In contrast to [3] that proposes an automatic creation of new protocols, the goal of this paper is to demonstrate how a more formal representation of existing protocols can be used to automatically generate an optimal protocol with optimal parameters for different applications.

The original contributions of this paper are three: First, we introduce the novel idea of MAC protocol engine and the procedure of choosing automatically the optimal protocol through the analysis of implemented protocols in the engine. Second, we illustrate the implementation of MAC protocol engine in SPINE software framework which has been created to decrease development time of WSNs for health care applications and improve interoperability by providing libraries, utilities and data processing functions. Third, we introduce the novel analysis of the unslotted IEEE 802.15.4 protocol to be used in the illustration of SPINE MAC Protocol Engine.

The rest of the paper is organized as follows: In Section II, a review of MAC protocols is presented. In Section III, the MAC protocol engine is described in more detail. Section IV illustrates the implementation of MAC protocol engine in the software framework called SPINE designed for health care applications by introducing the analysis of protocols and the implementation results. Section V concludes the paper.

II. MAC Protocols for Sensor Networks

MAC Protocols for sensor networks fall into two categories: schedule-based protocols and contention-based protocols. Schedule-based protocols avoid interference by scheduling nodes onto different sub-channels that are divided either by time, frequency or orthogonal codes. In each slot, a non-conflicting set of nodes are allowed to transmit. Schedule-based protocols are more power efficient since they allow the nodes to enter inactive states until their allocated slots. However, they require complex control mechanisms for discovering the topology and keeping the nodes synchronized [1] and running the schedules efficiently [4].

Contention-based protocols on the other hand are based on competing for a shared channel rather than pre-allocating transmissions. A common MAC protocol used for sensor networks is the IEEE 802.15.4 standard [5]. The protocol is designed to minimize the energy consumption at the transmitter. On the other hand, to minimize the energy consumption at the receiver, idle listening should be minimized since it does not contribute to the operation of the network, yet it may require a relatively large amount of energy. Duty-cycling has been proposed as an effective mechanism for reducing idle listening. Duty-cycling MAC protocols are of two types: synchronous and asynchronous. Synchronous protocols, such as SMAC [6] and TMAC [7], are based on negotiating a schedule among the neighboring nodes to specify when the nodes are awake and asleep. Asynchronous protocols such as BMAC [8] and X-MAC [9] are based on preamble sampling. In these methods, the receiver wakes up periodically to check whether there is a transmission and the sender, instead of coordinating the neighborsŠ wake up times, sends a preamble that is long enough to ensure the receiver wakes up during the preamble.

As we move from schedule-based protocols to contention-based protocols, the reliability for packet transmissions decreases due to probabilistic channel access. However, the scalability and adaptivity of the system is better due to dynamic allocation of resources. Moreover, although the energy saving decreases due to unscheduled access, there is less overhead for synchronization and scheduling. The trade-off between these two energy terms depends on network topology, data generation rate and physical layer constraints.

III. MAC Protocol Engine

The MAC protocol engine contains a library of protocols. Any MAC protocol developed for sensor networks can be included in this library. The engine takes as input the network topology and packet generation rate, the application requirements for energy consumption, delay and reliability, and the resource constraints from the underlying physical layer such as energy consumption and data rate. The protocol engine then chooses the optimal protocol among its library with optimal parameters for the specific topology, packet generation rate taking into account the corresponding physical layer technology and hardware for data rate and energy consumption satisfying constraints for energy, delay and reliability.

The implementation of MAC protocol engine requires the analysis of the protocols in the library. The library can include any subset of protocols described in Section II. The analysis should be provided for specifications and constraints we are interested in. The procedure of implementing a MAC protocol engine include the following steps:

1) Analysis of protocols in the library: The protocol performance is derived for the specific application requirements of energy, delay and reliability.
2) Validation of analysis: The formulations for the protocol performance are validated through analysis, simulation, and implementation.
3) Optimal Protocol Selection: The regions where each protocol is optimal for a specific energy, delay and reliability requirement is determined to be used in protocol selection.

IV. Case Study: SPINE

In this section we illustrate the idea of MAC protocol engine for the case of SPINE software for health care applications.

Sensor networks are expected to drive a health care revolution by providing outpatient monitoring, chronic disease management and elderly care. The wide range of applications include assisted living, activity recognition, fitness,

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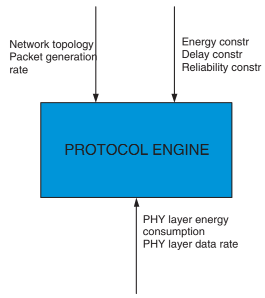

Fig. 1. Protocol Engine.

gait analysis, ergonomics and emotion recognition. Designing health care applications is too difficult and time consuming due to the lack of proper abstractions. SPINE software platform has been created to decrease development time and improve interoperability by providing libraries, utilities and data processing functions [10].

In health care applications, the network includes many sensor nodes placed on multiple places in the body and one coordinator node. The coordinator manages the network, collects and analyzes the data received from the sensor nodes, and acts as a gateway to connect the body area network to wide area networks for remote data access. The coordinator node is usually connected to a cell phone or PDA so is not energy limited whereas the sensor nodes are energy constrained due to the limited battery power. Currently SPINE supports WSNs with star topology, where sensor nodes communicate only with the coordinator although the framework can be easily extended to also support multi-hop communication and direct communication among sensor nodes.

The MAC protocol engine in SPINE includes two protocols: Time Division Multiple Access (TDMA) and IEEE 802.15.4. Therefore, we first propose a novel analysis of these protocols for the star topology supported by SPINE, and then validate and demonstrate how the engine chooses the optimal protocol under different application scenarios via the implementation in TinyOS.

In the next subsections, we propose a novel analysis of the IEEE 802.15.4 Unslotted Random Access Mechanism [5] and of a TDMA MAC protocol. The analysis aims at deriving the reliability, delay and energy consumption expressions of the MAC protocols. We then show how such an analysis is exploited by our protocol engine.

A. Analysis of Unslotted IEEE 802.15.4

Here we propose an analysis of the unslotted IEEE 802.15.4 random access. Main original contributions of such an analysis, with respect to the slotted 802.15.4 random access analysis [11], are the modelling of single channel access and the misalignment across the slots of different nodes. The goal of the analysis is to derive expressions for the probability that a packet is successfully received, the delay in the packet delivery, and the average energy consumption.

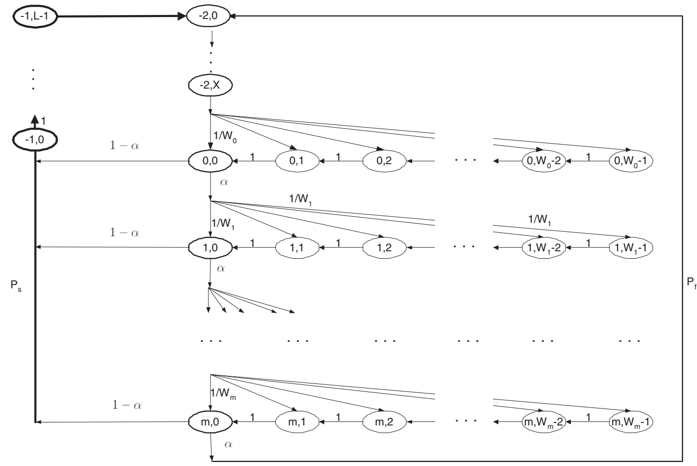

Fig. 2. Markov Model for IEEE 802.15.4 Unslotted Random Access.

The analysis requires finding a set of equations that define the optimal network operating point uniquely. We give details in the sequel.

In the unslotted IEEE 802.15.4 carrier sense multiple access with collision avoidance (CSMA/CA) mechanism, each device in the network has two variables: NB and BE. NB is the number of times the CSMA/CA algorithm is required to backoff while attempting the current transmission. NB is initialized to 0 before every new transmission. BE is the backoff exponent, which is related to how many backoff periods a device must wait before it attempts to assess the channel. The algorithm is implemented using units of time called backoff periods. The parameters that affect the random backoff are $BE_{\min}$, $BE_{\max}$ and $NB_{\max}$, which correspond to the minimum and maximum of BE and the maximum of NB respectively.

The unslotted CSMA/CA mechanism works as follows. NB and BE are initialized to 0 and $BE_{\min}$ respectively (Step1). The MAC layer delays for a random number of complete back-off periods in the range 0 to $2^{BE} - 1$ (step 2) and then requests PHY to perform a CCA (clear channel assessment) (step 3). If the channel is assessed to be busy (step 4), the MAC sub-layer increments both NB and BE by one, ensuring that BE is not more than $BE_{\max}$. If the value of NB is less than or equal to $NB_{\max}$, the CSMA/CA must return to Step 2, else the CSMA/CA must terminate with a Channel-Access-Failure status. If the channel is assessed to be idle (Step 5), the MAC layer starts transmission immediately.

The analysis is developed in two steps. We first study the behavior of a single device by using a Markov model (Fig.2). From such a model, we obtain the stationary probability ϕ that the device attempts its carrier channel assessment (CCA). Second, we couple the per user Markov chains to obtain an additional set of equations that give the CCA assessments of other users. The solution of such a set of

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equations provides us with the per user ϕ and probability of free channel assessment.

We first develop the Markov model to determine ϕ, see Fig. 2. Let $c(t)$ be the stochastic process representing the counter for random delay and packet transmission duration. The integer time t corresponds to the beginning of the slot times. Let α be the probability of assessing channel busy during CCA. Next, when entering the transmission state, L slots should be counted, where L denotes the packet transmission duration measured in slots*. Let X denote the time duration to wait before the next transmission attempt measured in slots. Let $s(t)$ be the stochastic process representing the delay line stages representing the number of times the channel is sensed busy before packet transmission ($s(t) \in \{0, \cdots, NB\}$), or the transmission stage ($s(t) = -1$) at time t. The states ($s(t) = -2$) in Fig. 2 model unsaturated periodic traffic. We assume that the probability to start sensing is constant and independent of all other devices and of the number of retransmissions suffered. With this assumption, $\{s(t), c(t)\}$ is the two-dimensional Markov chain of Fig. 2 with the following transition probabilities:

$$P\{i,k|i,k+1\} = 1,\ k \geq 0 \quad (1)$$

$$P\{0,k|i,0\} = \frac{1-\alpha}{W_0},\ i < NB \quad (2)$$

$$P\{i,k|i-1,0\} = \frac{\alpha}{W_i}, \qquad i \leq NB, k \leq W_i - 1 \quad (3)$$

$$P\{0,k|NB,0\} = \frac{1}{W_0}. \quad (4)$$

In these equations, the delay window W_i is initially $W_0 = 2^{BE_{\min}}$ and doubled any stage until $W_i = W_{max} = 2^{BE_{\max}}, (BE_{\max} - BE_{\min}) \leq i \leq NB$. Equation 1 is the condition to decrement the delay line counter per slot. Equation 2 states that it is only possible to enter the first delay line from a stage that is not the last one ($i < NB$) after sensing the channel idle and hence transmitting a packet. Equation 3 gives the probability that there is a failure on channel assessment and the station selects a state in the next delay level. Equation 4 gives the probability of starting a new transmission attempt when leaving the last delay line, following a successful or failed packet transmission attempt.

Denote the Markov chain steady-state probabilities by $b_{i,k} = P\{(s(t), c(t)) = (i,k)\}$, for $i \in \{-1, NB\}$ and $k \in \{0, \max(L-1, W_i - 1)\}$. Using Equation 3, we have

$$b_{i-1,0}\alpha = b_{i,0}\,, 0 < i \leq NB,$$

which leads to

$$b_{i,0} = [\alpha]^i b_{0,0}\,, 0 < i \leq NB.$$

From Equations (1)– (4) we obtain

$$b_{i,k} = \frac{W_i - k}{W_i}\left[(1-\alpha)\sum_{j=0}^{NB} b_{j,0} + \alpha b_{NB,0}\right] \quad \text{for } i = 0,$$

$$b_{i,k} = \frac{W_i - k}{W_i} b_{i,0}, \quad \text{for } i > 0.$$

Since the probabilities must sum to 1, it follows that

$$\begin{aligned} 1 &= \sum_{i=0}^{NB}\sum_{k=0}^{W_i-1} b_{i,k} + \sum_{i=0}^{L-1} b_{-1,i} + \sum_{i=0}^{X-1} b_{-2,i} \\ &= \sum_{i=0}^{NB} b_{i,0}\left[\frac{W_i+1}{2} + (1-\alpha)L + (1-\alpha)X\right] \\ &\quad + b_{NB,0}\alpha X. \end{aligned}$$

By substituting the expression for W_i, we obtain

$$\begin{aligned} 1 = \frac{b_{0,0}}{2}\Bigg\{&[1 + 2(1-\alpha)(L+X)]\frac{1-\alpha^{NB+1}}{1-\alpha} \\ &+ 2X\alpha^{NB+1} + 2^{diffBE} W_0 \frac{\alpha^{diffBE+1} - \alpha^{NB+1}}{1-\alpha} \\ &+ W_0 \frac{1 - (2\alpha)^{diffBE+1}}{1 - 2\alpha}\Bigg\} \end{aligned} \quad (5)$$

where $diffBE = BE_{\max} - BE_{\min}$. The transmission failure probability P_f is

$$P_f = b_{NB,0}\alpha, \quad (6)$$

and the probability that a node starts to transmit is

$$\tau = P_s = \phi(1-\alpha),$$

in which

$$\phi = \phi_1 = \sum_{i=0}^{NB} b_{i,0} = b_{0,0}\frac{1-\alpha^{NB+1}}{1-\alpha}. \quad (7)$$

We have now derived one expression for ϕ from the per user Markov models. By determining the interactions between users on the medium, we will now derive expressions for α. Assume that there are N nodes in the network. Denote by $M(s) = -1$ the event that there is at least one transmission in the medium by another node and assume that, without loss of generality, the sensing node is i_N, which is denoted as $S^{i_N}(c) = -1$ if $S^i(s) = -1$ is the event that node i is transmitting. Then, the probability that a node sensing the channel finds it occupied is $\alpha = \Pr(M(s) = -1|S^{i_N}(c) = -1)$, which is computed as follows

$$\begin{aligned} \alpha &= \Pr(M(s) = -1|S^{i_N}(c) = -1) \\ &= \sum_{n=0}^{N-2}\begin{pmatrix} N-1 \\ n+1 \end{pmatrix}\Pr\left(\bigcap_{k=1}^{n+1} S^{i_k}(s) = -1|S^{i_N}(c) = -1\right) \\ &= \sum_{n=0}^{N-2}\begin{pmatrix} N-1 \\ n+1 \end{pmatrix}\Pr\left(S^{i_1}(s) = -1\right) \\ &\quad \times \Pr\left(\bigcap_{k=2}^{n+1} S^{i_k}(s) = -1|S^{i_1}(s) = -1, S^{i_N}(c) = -1\right). \end{aligned} \quad (8)$$

The probability that node i_1 is transmitting is

$$\Pr(S^{i_1}(s) = -1) = (L+1)P_s = (L+1)\phi(1-\alpha), \quad (9)$$

*We assume that this duration is an integer number of slots in the paper.

which requires the node to sense (with probability ϕ) before transmission and the following slot to be empty (with probability $(1-\alpha)$). It is $(L+1)$ instead of L due to the misalignment in the slots of the nodes i_1 and i_N in the unslotted 802.15.4 protocol.

To express the conditional probability in terms of ϕ, the transmission pattern needs to be understood: If there was no difference between sensing the channel and starting the transmission, then in the unslotted case no two nodes would be transmitting simultaneously since the probability that two nodes start sensing simultaneously in the continuous case is zero. However, since there is a finite time between channel sensing and starting transmission, we assume that in the worst case, if two or more nodes start sensing in the same slot (slots are considered the same if the difference between their starting time is minimal), even if they are misaligned, the transmissions start at the same slot. The conditional probability is hence equivalent to

$$\Pr\left(\bigcap_{k=2}^{n+1} S^{i_k}(s)=-1 \mid S^{i_1}(s)=-1, S^{i_N}(c)=-1\right) \simeq \Pr\left(\bigcap_{k=2}^{n+1} S^{i_k}(c)=-1 \mid S^{i_1}(c)=-1, S^{i_N}(c)=-1\right) \tag{10}$$

Since we assumed that the probability ϕ to sense in a given slot is independent across nodes, we can easily see that this is

$$\Pr\left(\bigcap_{k=2}^{n+1} S^{i_k}(c)=-1 \mid S^{i_1}(c)=-1, S^{i_N}(c)=-1\right) = \phi^n(1-\phi)^{N-2-n}, \tag{11}$$

which requires nodes $i_2, ..., i_{n+1}$ to sense and the remaining $N-2-n$ nodes not to sense in the sensing slot of i_1. As a result,

$$\alpha = (L+1)[1-(1-\phi)^{N-1}](1-\alpha). \tag{12}$$

From this, we can derive a second expression for ϕ:

$$\phi_2 = 1-\left[1-\frac{\alpha}{(L+1)(1-\alpha)}\right]^{\frac{1}{N-1}}.$$

The network operating point as determined by ϕ and α is given by solving the two non-linear Equations (7), (12).

We are now in the position to give the expression of the reliability. Recall that the reliability is defined as the probability of packet success. To have a successful packet transmission, the channel should be sensed idle when none of the other nodes is sensing the channel. The reliability is then given by the following simple expression:

$$\begin{aligned} R &= \sum_{i=0}^{NB}(1-\phi)^{N-1}(1-\alpha)\alpha^i \\ &= (1-\phi)^{N-1}(1-\alpha^{NB+1}). \end{aligned} \tag{13}$$

The average delay for the node, given that the packet is successfully transmitted, is given as follows:

$$D = \left[\sum_{i=0}^{NB}\left(\sum_{k=0}^{i}\frac{W_k+1}{2}\right)\frac{\alpha^i(1-\alpha)}{1-\alpha^{NB+1}}+L\right]r_s,$$

where r_s is the slot duration. Finally, the average energy consumption is given by the following expression:

$$\begin{aligned} E = &P_l\left(\sum_{i=0}^{NB}\sum_{k=1}^{W_i-1} b_{i,k} + \sum_{i=0}^{NB} b_{i,0}\right) + P_t\sum_{i=0}^{L-1} b_{-1,i} \\ &+ P_s\sum_{i=0}^{X-1} b_{-2,i}. \end{aligned} \tag{14}$$

where P_l, P_t and P_s are the average energy consumption in idle-listen, transmit and sleep states respectively. We assume that the radio is put in idle-listen state during the random backoff.

B. Analysis of TDMA Protocol

In TDMA MAC protocols, we assume that N time slots are assigned to N nodes in the network. The nodes are synchronized with a predetermined synchronization packet transmission frequency f_s. Each slot is long enough to accommodate guard time to account for synchronization errors and one packet transmission. The length of guard time is a function of f_s.

The average delay of packet is given as follows:

$$D = \frac{N}{2}t_s + t_p = \frac{N}{2}\left(\frac{d}{f_s}+2t_p\right) \tag{15}$$

where t_s is the duration of TDMA slot, d is the clock drift per unit time and t_p is the packet transmission time, which corresponds to L times the slot time r_s in the previous notation.

The reliability of TDMA schemes is approximately 1 assuming appropriate transmit radio powers are used and ignoring the interference from other networks.

The average energy consumption is given as follows:

$$E = P_rLr_sf_s + P_t\frac{L}{L+X} + P_s\left(1-\frac{L}{L+X}-Lr_sf_s\right) \tag{16}$$

based on the assumption that $L/(L+X)+Lr_sf_s \leq 1$.

C. Analysis Validation

To benchmark the theoretical framework presented above we implemented the two MAC protocols by using the software framework SPINE for health care applications, which runs on top of TinyOS 2.x [12] and Tmote Sky sensor nodes [13]. In both the simulation and the experimental implementation we choose the default parameters for IEEE 802.15.4, namely $BE_{\min}=3$, $BE_{\max}=5$, $NB=4$, $f_s=1/30Hz$ and $d=40\mu s$ per second unless otherwise

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TABLE I
IEEE 802.15.4 MAC SPECIFICATIONS

Parameter	Values
$BE_{\min}$	[3 4 5 6 7 8]
$BE_{\max}$	[3 4 5 6 7 8]
NB	[0 1 2 3 4]

stated. Nodes were placed at few meters from the cluster-head, and in line of sight.

Figure 3 shows the delay as obtained by analysis and experiments for different number of nodes, whereas Figure 4 gives the delay for different packet generation periods. The delay increases considerably for TDMA systems as the number of nodes increases. On the other hand, the delay is almost constant for IEEE 802.15.4 especially at low packet generation rates. The curves achieved by our analysis match quite well the experimental behavior. The slight difference between analysis and simulations is due to the unavoidable measurements delay in the TinyOS protocol stack.

Figure 5 shows the reliability for different number of nodes whereas Figure 6 gives the reliability for different packet generation periods as obtained by our analysis and experiments. The reliability is approximately 1 for TDMA MAC, except the small amount of packet losses in the experiments due to mainly rare channel attenuations and imperfect synchronization. The reliability is very close to 1 for random access schemes when the packet generation rate and number of nodes is low.

Figure 7 shows the energy for different number of nodes whereas Figure 8 gives the energy for different packet generation periods as obtained by analysis, cfr. (14) and (16), and experiments. The energy consumption of TDMA systems is better than random access protocols when the packet generation rate is very high and the number of nodes increases. However, as the packet generation rate decreases, the random access protocol performs better since there is no synchronization overhead. The small difference with the experimental results reflects the inaccuracies in the delay measurements, as we observed from the delay evaluation.

D. Optimal Protocol Selection

In this section, we illustrate the selection of the optimal MAC by the MAC engine. Here, the optimal MAC is defined as the one that minimizes the energy consumption for certain reliability and delay constraints.

Figure 9 shows the optimal MAC chosen by the protocol engine for a network of $N = 3$ nodes and a packet generation period $P = 20\ ms$. The TDMA MAC is the optimal solution when the delay constraint is greater than $10\ ms$. The parameter configuration for IEEE 802.15.4 MAC parameters that minimizes the energy consumption are $BE_{\min} = 3$, $BE_{\max} = 3$ and $NB = 0$, but when the reliability constraint is greater than 95%, this solution is infeasible and the best solution has $NB = 1$ or $NB = 2$ when the reliability is

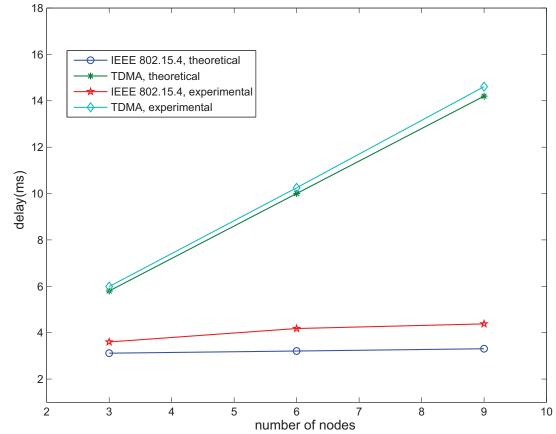

Fig. 3. Experimental validation: delay for different number of nodes, with packet generation period $P = 20\ ms$.

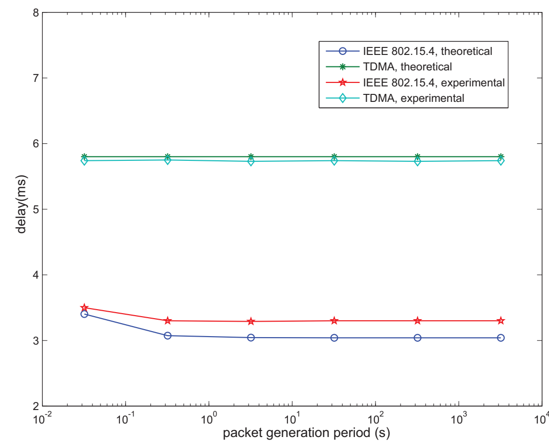

Fig. 4. Experimental validation: delay for different packet generation periods, with $N = 3$.

close to 99%. By increasing the number of nodes till $N = 9$ (see Figure 10), we see that the only feasible solutions with reliability greater than 95% are those with $NB = 4$, and higher backoff exponents.

In Figure 11 we report the results for a scenario with $N = 9$ and $P = 20$ s. As we discussed in the previous section, the TDMA solution is not efficient with very low packet generation rate, because of the synchronization overhead. We observe that among the IEEE 802.15.4 MAC parameters, the best solution has $BE_{\min} = 3$, $BE_{\max} = 3$ and $NB = 0$.

V. CONCLUSION

We presented a MAC engine, a novel approach to MAC protocol design based on selecting the optimal protocol with optimal parameters among a library of protocols in the protocol engine. The idea is to automate this selection based on the analysis of each protocol available in the engine. This procedure eliminates the need to restart the process of designing a MAC protocol for each possible application. The

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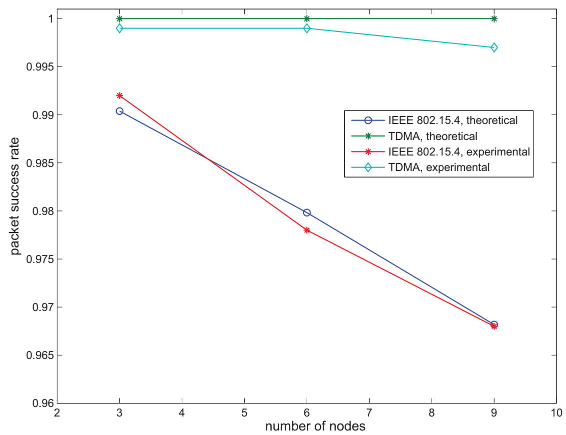

Fig. 5. Experimental validation: reliability for different number of nodes, with packet generation period $P = 20\ ms$.

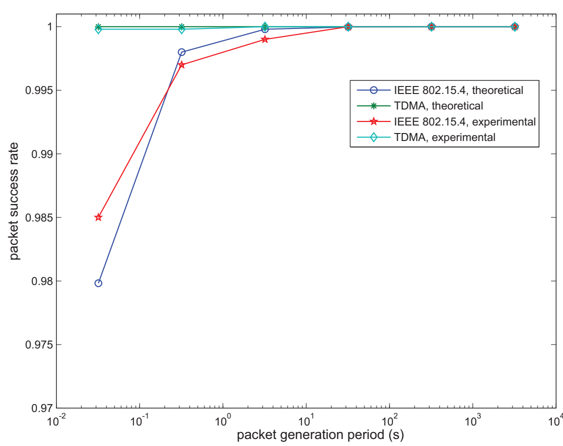

Fig. 6. Experimental validation: reliability for different packet generation period, with $N = 3$.

MAC engine takes as input the application specifications (network topology and packet generation rate), the application requirements for energy consumption, delay and reliability, and the constraints from the underlying physical layer (energy consumption and data rate). The protocol engine then chooses the optimal protocol among its library with optimal parameters. The implementation of MAC protocol engine was illustrated in the software framework called SPINE designed for health care applications. Two prominent MAC protocols used for health care applications, IEEE 802.15.4 unslotted random access and Time Division Multiple Access (TDMA), were analyzed. Next, the analysis was validated via the implementation in TinyOS. The analysis was then used to demonstrate the process of choosing the optimal protocol under different application scenarios. We believe that this opens a new research area for the analysis of more complex protocols.

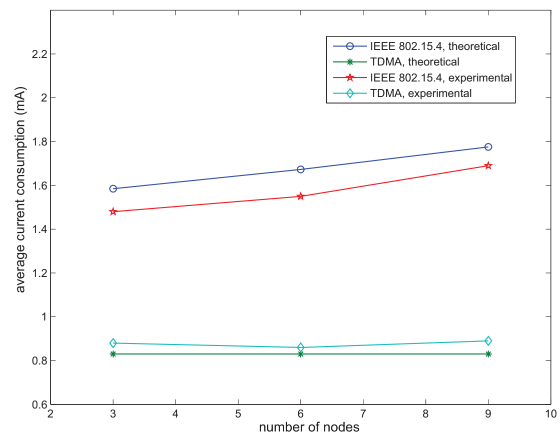

Fig. 7. Experimental validation: average energy consumption for different number of nodes, with packet generation period $P = 20\ ms$.

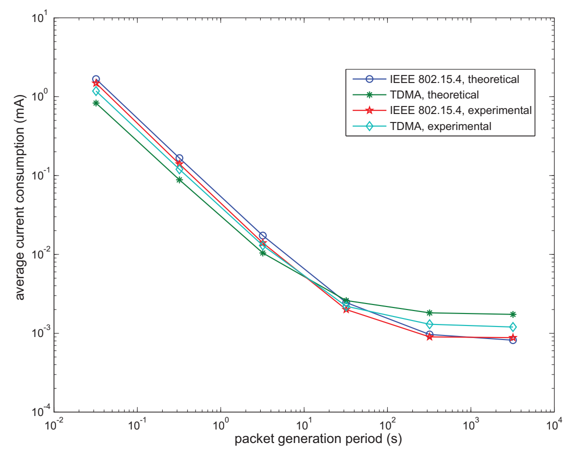

Fig. 8. Experimental validation: average energy consumption for different packet generation period, with $N = 3$.

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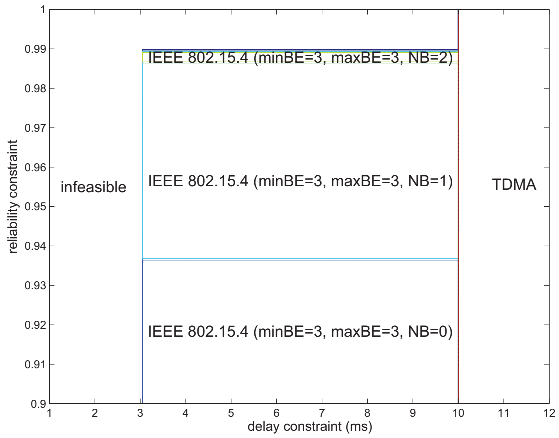

Fig. 9. MAC Protocol Engine with $N = 3$ and $P = 20\ ms$.

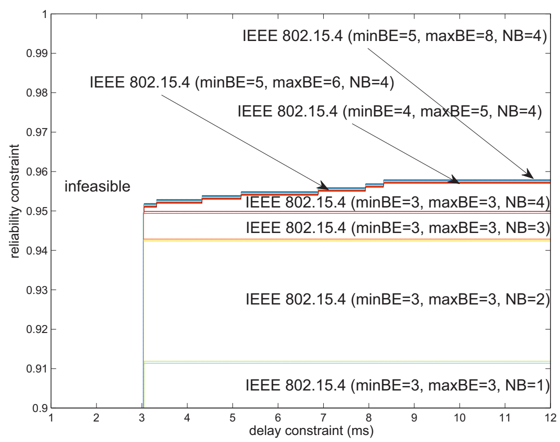

Fig. 10. MAC Protocol Engine with $N = 9$ and $P = 20\ ms$.

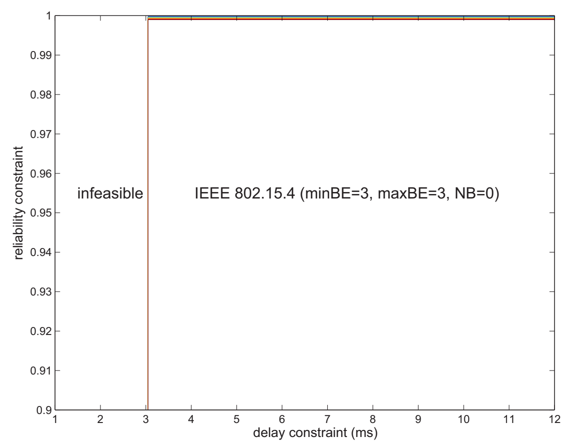

Fig. 11. MAC Protocol Engine with $N = 9$ and $P = 20\ s$.

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978-1-4244-4148-8/09/$25.00 ©2009
This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE "GLOBECOM" 2009 proceedings.