# A Hybrid Contention/Reservation Medium Access Protocol for Wireless Sensor Networks

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***Abstract*—Most Wireless Sensor Networks (WSNs) applications require that a large number of low-complexity energy-constrained sensors forward the sensed information to a sink node, which gathers, processes and forwards the information to the end-user. Although, this approach is beneficial for the sensor nodes, since most of the complexity is delegated to the sink node, it is also the origin of severe bottleneck effects near to sink. Having a large number of sensors trying to forward their data to a single sink node leads to increased traffic intensity, congestion and increased packet loss probabilities. The key point in coping with this problem is the medium access control (MAC) protocols that handle the sensors' traffic, with respect to specific performance optimization criteria. Following the general research trend, which focuses on hybrid contention/reservation MAC protocols, we present a novel hybrid protocol, which decides on the access mode to be used, based on the trade-off between the expected throughput and protocol complexity. The expected throughput can be predicted by exploiting an analytical framework grounded on the queueing theory, which evaluates the performance of both contention based and contention-free access schemes. Extensive system simulation results validate the theoretical derivations and the ability of the proposed hybrid MAC scheme to balance between performance and complexity.**

***Index Terms*—Contention-based MAC, contention-free MAC, hybrid MAC, queueing theory, throughput, WSN.**

## I. INTRODUCTION

In typical Wireless Sensor Network (WSN) applications there are two major type of devices: the sensor nodes, which collect specific information from the environment, and the sink nodes that gather this information from the sensors in order to process and forward it to the end-user. Given the constraints of sensor nodes, such as the energy efficiency, cost and complexity, this approach simplifies the tasks of the sensors, but it also concentrates most of the traffic near the sink, increasing the chance of bottle-neck effects. This leads to increased transit traffic intensity, congestion and higher packet loss probabilities, or equivalently to wasted energy and bandwidth. As a result, the sensors that are located near the sink (in the so called intensity region), lose a larger number of packets and consume significantly more energy than sensors further away from it, shortening the operational lifetime of the overall network. Hence, mitigating the negative consequences of this bottleneck effect is considered as an important challenge and thus represents the main focus of our research.

### A. Related Work

Due to the particular requirements of WSNs, many challenges are encountered including resource constraints, node deployment, topology changes, scalability, unbalanced traffic etc [1]. An important factor, which highly depends on these issues, is related to the performance of the medium access protocol (MAC) that is utilized. In this context three main categories of MAC protocols can be found, namely contention-based MAC protocols, (e.g., Sensor-MAC (S-MAC) [2], Timeout-MAC, (T-MAC) [3], B-MAC [4]), contention-free protocols, (e.g., $\mu$-MAC [5], traffic-adaptive medium access protocol (TRAMA) [6]), and hybrid schemes, (e.g., Zebra-MAC (Z-MAC) [7], Funneling MAC (F-MAC) [8], carrier sensing multiple access (CSMA)/time division multiple access (TDMA) [9], [10]). More specifically, focusing on the hybrid approaches in [8] a hybrid CSMA/TDMA scheme was designed for the intensity region that is supervised by the sink using on demand beaconing. In [9], considering a multihop communication scenario, a traffic scheduling strategy is proposed for improving the network capacity, fairness and packet loss. Finally, in [10], based on the 802.15.4 standard [11], an adaptive hybrid CSMA/TDMA protocol was presented, which dynamically assigns a part of contention access period to TDMA and shares this period among nodes with more packets in their buffer. A common observation in all these approaches is that contention-based access is used for relatively low traffic conditions, while contention-free slot assignments become dominant as traffic density increases. However, it is not a trivial task to identify the switching point between the contention-based and contention-free access, which optimizes the system performance in terms of throughput and energy efficiency.

### B. Contribution

Our contribution is this area is two fold:

- we provide an analytical framework for evaluating the performance of contention-based and contention-free access schemes, and
- we propose a hybrid access scheme that incorporates the advantages of both approaches.

More specifically, based on queueing theory, we provide exact and/or approximate expressions for evaluating the performance of the access schemes under consideration, in terms

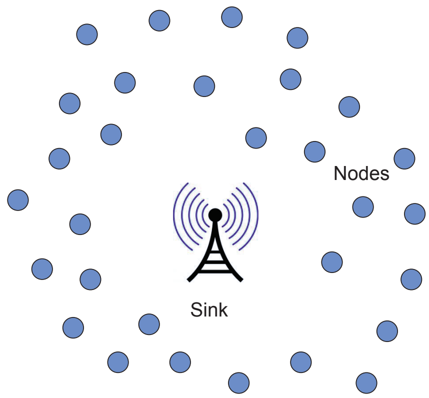


Fig. 1. Communication scenario: distributed energy-limited nodes communicating to a sink.

of packet loss probability and throughput. These expressions can be found quite useful for predicting the performance of contention-free or contention-based access schemes and thus deciding on the more suitable one. Furthermore, based on these theoretical expressions, a switching criterion between the contention- and reservation-based access is proposed, enabling the introduction of a hybrid approach for accessing the medium.

The remainder of this paper is organized as follows. In Section II the network modeling in presented, while in Section III analytical results for the contention-based and contention-free access are provided together with some performance comparison results. In Section IV, a hybrid MAC protocol is presented and some selected simulated performance results are given, while in Section V the concluding remarks of this paper can be found.

## II. Network Modeling

We investigate the case where a number of devices are simultaneously trying to set up a communication link with the data collector, in an one hop manner, which in our case will be denoted as the sink (see Fig. 1). We assume that the wireless communication links between the nodes and the sink are not subject to errors, which means that every successful packet reception is perfectly decoded.

The majority of the MAC protocols are based on contention-free or contention-based access to the medium. In case of contention-based protocols, the nodes are trying to gain access to the medium by sensing the channel for activity and if no activity is detected they initiate a connection procedure. Based on the fact that no predetermined time slot is assigned to them, several clear advantages have been identified and reported, including the simpler implementation, the scalability and the ability to efficiently handle sporadic traffic. However, contention-based protocols suffer from collisions, as the traffic load increases, causing increased latency, more retransmissions and hence higher energy consumption. In case of contention-free protocols each node has a pre-assigned time slot, where only that particular node is allowed to transmit. Hence, a time division scheme is employed to schedule nodes when they are able to have access to the channel for transmission. The drawbacks of the scheduled access include tight synchronized procedures, coordination by a certain node, initialization before the channel utilization.

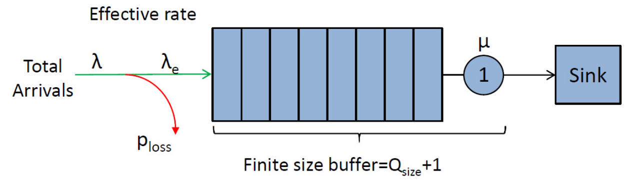


Fig. 2. $M/D/1/K$ queueing model.

In our analysis, we model our system using the $M/D/1/K$ queuing model with a single server and finite buffer size at each sensor node, which is in alignment with the low-complexity requirement of the sensor nodes. The stability of the model is ensured by assuming small size of data packets, while control messages are assumed to be sent in extra time slots [9], [12]. In the M/D/1/K queueing model, with queue size $Q_{\text{size}}$ packets, the traffic intensity is defined as

$$\rho = \frac{\lambda}{\mu}, \tag{1}$$

where $\lambda$ is the rate of the packet arrival process that following the Poisson distribution and $\mu$ represents the service time which in our case is equal to 1. In Fig. 2, following a similar approach as in [13], the considered $M/D/1/K$ system model is illustrated for a tagged node trying to communicate with the sink. It is noted that for the specific case of one node, the average throughput, $\overline{S}$ observed in the sink is equal to

$$\overline{S} = \lambda(1 - p_{\text{loss}}), \tag{2}$$

where $p_{\text{loss}}$ denotes the packet loss probability and will be investigated next for various medium access policies.

## III. Reservation-Based vs Contention-Based MAC Protocols

In this section, an analytical framework is developed for evaluating the performance of the reservation and contention-based MAC schemes, in terms of the expected throughput and the packet loss probability. The packet loss probability of the $M/D/1/K$ system can be closely approximated by [14]

$$p_{\text{loss}} = \frac{(1-\rho)\, g_K}{1 - \rho\, g_K} \tag{3}$$

where

$$g_K = 1 - \sum_{i=0}^{Q_{\text{size}}} \pi_i^{(\infty)} \tag{4}$$

and $K = Q_{\text{size}} + 1$. In (4), $\pi_i^{(\infty)}$ denote the recursive formulas for the queue length distribution of an infinite buffer system and are defined as

$$\pi_i^{(\infty)} = \begin{cases} 1-\rho, & \text{if } i = 0 \\ \frac{1}{1-\alpha_0}\left(\alpha_{i-1}\pi_0^{(\infty)} + \sum_{j=1}^{i-1} \alpha_{i-j}\pi_j^{(\infty)}\right), & \text{if } i > 0 \end{cases} \tag{5}$$

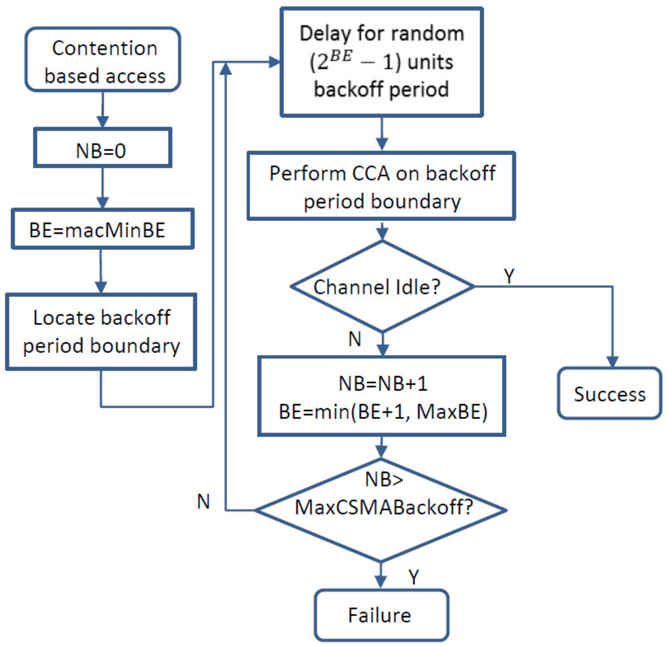


Fig. 3. Mode of operation of the contention-based access scheme.

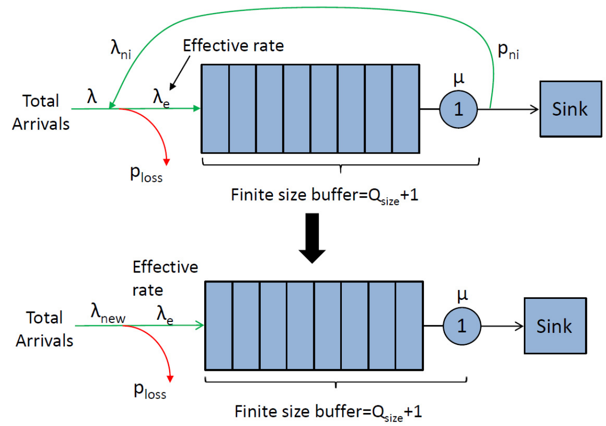


Fig. 4. System model in case of parallel transmissions.

where

$$\alpha_i = \begin{cases} \alpha_{i-1} - \frac{(\lambda \overline{s})^i \exp(-\lambda \overline{s})}{i!}, & \text{if } i > 0 \\ 1 - \frac{(\lambda \overline{s})^i \exp(-\lambda \overline{s})}{i!}, & \text{if } i = 0. \end{cases} \quad (6)$$

In (6), $\overline{s}$ represents the service time $\overline{s} = \text{PacketSize}/\text{BW}$ and in our case it is considered to be constant and equal to 1.

### *A. Reservation-based MAC*

Regarding the reservation-based MAC we assume sensor nodes with finite buffer size, perfect synchronization between the sink and the nodes, while hidden nodes do not exist. Given these assumptions, the packet loss probability and the throughput can be directly derived from the corresponding expressions of the $M/D/1/K$ model.

*1) Packet loss probability:* The loss probability, for each node, is equal to

$$p_{\text{loss}_{\text{Res}}} = \frac{(1-\rho)\, g_K}{1 - g_K \rho} \quad (7)$$

*2) Throughput:* The throughput of reservation-based MAC, for each node, can be obtained as in (2), using (7), i.e.

$$\overline{S}_{Res} = \lambda(1 - p_{\text{loss}_{\text{Res}}}). \quad (8)$$

### *B. Contention-based MAC*

In the case of the contention-based MAC two distinct cases are investigated, 1) the case with hidden terminals and 2) the case without hidden terminals. In both cases the mode of operation that has been considered is illustrated in Fig. 3. This mode of operation is based on the fact that all devices may retain in their memory a small number of variables, such as the number of backoffs (NB), the backoff exponent (BE)m the MaxCSMABackoff and the MaxBE. Specifically, NB is backoff time before attempting to access the medium. Its initial value is equal to zero and it gradually increases as long as the medium is sensed active, until it exceeds a maximum value (MaxCSMABackoff), which results in dropping the packet. Moreover, BE determines the number of backoff periods that a device should wait before attempting to access the channel and in our case is initialized to 1. Finally, MaxBE denotes the maximum allowed value for BE.

*1) Hidden Node Scenario:* In this scenario the nodes are not able to detect transmissions from other nodes due to the well-known hidden node effect.

*a) Packet loss probability:* The packet loss probability, $p_{\text{loss}_{\text{Con}}}$, for each node, is equal to (3).

*b) Throughput:* In this scenario, the probability that other nodes are simultaneously transmitting during the transmission of the tag node is given by [15]

$$p = 1 - (1 - \tau)^{n-1} \quad (9)$$

where $n$ is the number of nodes that actively compete for channel access and $\tau$ represents the packet transmission probability, obtained in our case as

$$\tau = \lambda(1 - p_{\text{loss}_{\text{Con}}}). \quad (10)$$

Considering the case where the nodes are not able to detect transmissions from other nodes, due to the hidden node effect, $p$ also represents the collisions probability and hence using (9), the throughput can be obtained as

$$\overline{S}_{Con} = \lambda(1 - p_{\text{loss}_{\text{Con}}})(1 - p). \quad (11)$$

*2) Non-Hidden Node Scenario:* In this scenario, all nodes are able to detect other nodes' transmissions, and hence simultaneous transmissions, which would result in packet collisions, can be avoided in all cases. As soon as a node detects that the medium is busy, it backs off, for a random amount of time, and then retries. Let us assume that the probability of sensing the channel as non idle is $p_{ni}$. As stated in the previous section,

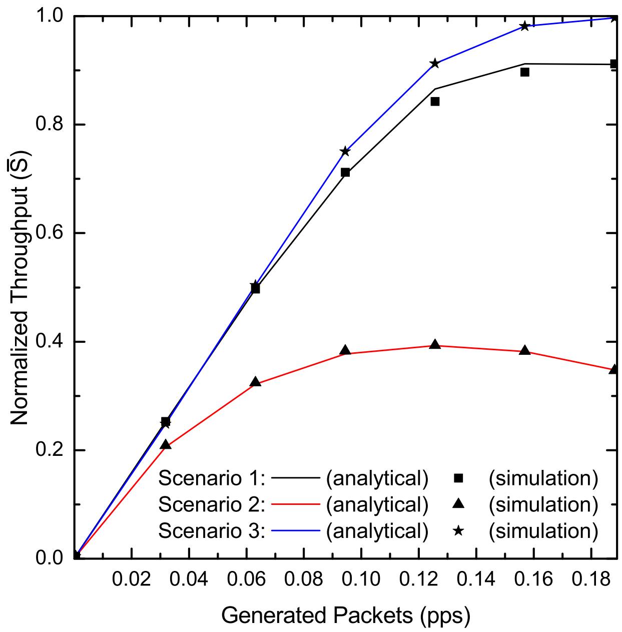


Fig. 5. Normalized Throughput performances vs the number of generated packets.

$p_{ni} = 1 - (1-\tau)^{n-1}$, with $\tau = \lambda(1-p_{\text{loss}})$. Furthermore, assuming that the probability of discovering the channel non idle, $p_{ni}$, is approximated by the Poisson distribution with probability mass function equal to

$$f(k;\lambda_{ni}) = P(X=k) = \frac{\lambda_{ni}^k \exp(-\lambda_{ni})}{k!} \tag{12}$$

with $X$ denoting a Poisson RV. Hence, $p_{ni} \cong 1 - P(X=0)$ and the parameter $\lambda_{ni}$ of the poisson-distributed probability of non idle time can be expressed as $\lambda_{ni} = -\ln(1-p_{ni})$. Therefore, more packets are added to the queue with rate $\lambda_{ni}$ and hence the total arrivals could be closely approximated with

$$\lambda_{new} \cong \lambda + \lambda_{ni}. \tag{13}$$

The system model for this scenario can be found in Fig. 4, where the new effective rate is depicted. For the new approximated arrival rate and considering the system model that is depicted in Fig. 4, a direct evaluation of the $p_{\text{loss}}$ and the throughput can be obtained.

*a) Packet loss probability:* The probability of loss is equal to (3), considering arrival rate $\lambda_{new}$.

*b) Throughput:* The throughput can be easily obtained using (2) and (13).

Next, the performance of the three previously mentioned modes of operation are studied in terms of both simulated and analytical results.

### C. Performance Comparison and Observations

Considering a network topology with 8 nodes that are simultaneously trying to communicate with the sink in an one hop manner, we investigate the performance of the network in terms of the normalized throughput ($\overline{S}$) both theoretically (using the previously derived analytical expressions) as well as via simulations. The system model under consideration includes three scenarios: contention-based access where a) the hidden node problem does not exist (Scenario 1) b) the hidden node problem exists (Scenario 2), c) contention-free access (Scenario 3). Furthermore, in all cases finite buffer size has been considered, while for the contention-based case we have set $BE = 1$ and $MaxBE = 6$, which is in alignment with the low-cost requirement of the sensor nodes. Fig. 5, depicts the close performance between Scenarios 1 and 3, while in case of Scenario 2 the throughput is considerable reduced due to the hidden node problem, which results in high packet collisions. Furthermore, a close agreement between the simulated and analytical results is clearly illustrated, while it is noted that the analytical results for Scenario 1 represent an approximation and not an exact solution. A useful observation from this analysis concerns the throughput performance of contention-free and contention-based access schemes which is quite close in the case of light and medium traffic conditions. Hence, a convenient approach is to employ contention-based access as long as the throughput difference (between contention based and contention-free) is below a predefined level, in order to capitalize on the advantages of contention-based schemes. Moreover, in case that the throughput difference exceeds this predefined level contention-free access should be preferred. In other words a hybrid access scheme seems to be the optimum solution in terms of scalability (when we have low or medium traffic) and throughput (for high traffic demands).

## IV. The Hybrid MAC Protocol

Following the previous analysis, it becomes clear that the performance of the contention and reservation-based MAC protocols can be predicted quite accurately given the network topology, the total traffic conditions and basic assumptions, such as the buffer size of the sensors. The goal of that analysis is to exploit the theoretical results towards a practical hybrid protocol, which will be able to choose the appropriate access mode. The basic concept underlying the proposed protocol is the utilization of a contention-based MAC as the default access scheme, unless the performance in terms of throughput falls below a predetermined value. Without loosing the generality of our approach we have assumed independent and identical distributed generated traffic by all the nodes, which results to an identical data arrival rate, $\lambda$, for all nodes.

### A. Mode of Operation

The scope of this hybrid protocol is to handle in an optimum way the heterogeneous traffic demands that may occur in a WSN. For instance, in case of light traffic conditions a simple contention-based access protocol could be utilized, while as traffic gradually increases a contention-free scheme would be preferable in order to maintain the performance. In this sense, we propose a hybrid access protocol with the mode of operation provided in Fig. 6. As it is depicted in this figure in case that the switching criterion is above a predefined threshold our algorithm employs contention-based

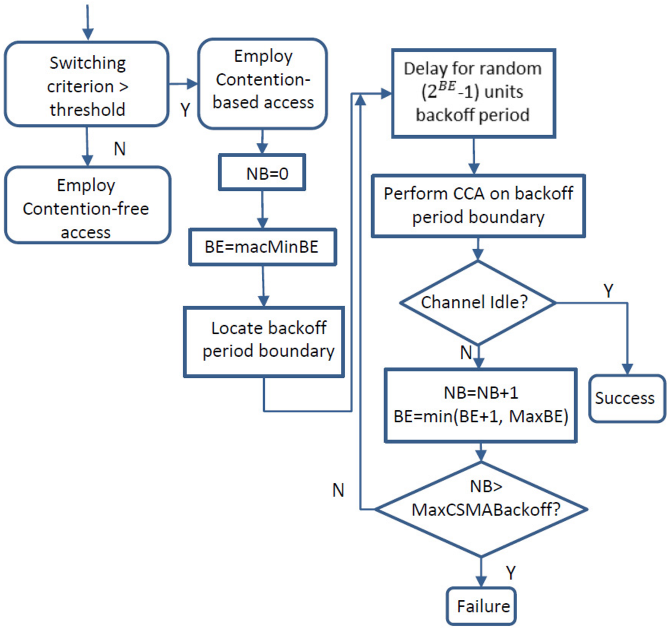


Fig. 6. Mode of operation of the proposed hybrid access scheme.

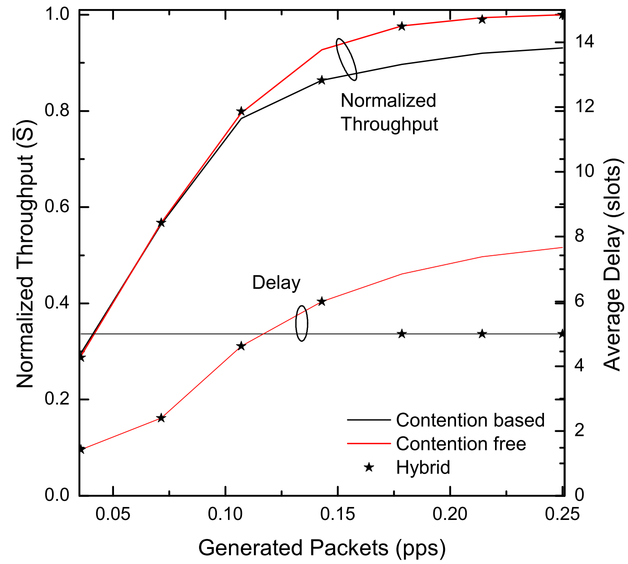


Fig. 7. Normalized Throughput performance vs number of generated packets.

access, otherwise it switches to contention-free access for improving the performance. The switching criterion selected that has been found to optimize the throughput is

$$\text{Switching criterion} = \frac{\overline{S}_{Con}}{\overline{S}_{Res}}. \tag{14}$$

The throughput performance results can be theoretically evaluated (predicted) at the sink using the previous derived analytical expressions and the corresponding value of $\lambda$, which, as mentioned previously, is considered to be identical for all nodes trying to communicate with the sink. This value for $\lambda$ can be communicated to the sink whenever there is a considerable variation in the generated traffic, using a few reserved bits in the data packets. Moreover, assuming a threshold value that is equal to $0.9$, yields the following operation mode: if the theoretically evaluated performance for the contention-based access scheme throughput is more than $90\%$ of the corresponding performance of the contention-free access, the proposed scheme should operate as a contention-based one, otherwise it should switch to a contention-free one. Hence, using such an approach a near optimum throughput performance is guaranteed, whilst depending upon the requirements, e.g., increased demands for the throughput, this threshold could be modified accordingly.

### *B. Results and Discussion*

The simulation setup includes a star network topology with $8$ nodes that are simultaneously trying to communicate with the sink node (in a one-hop way), utilizing either a contention-based, or a contention-free or the hybrid access protocols. In all cases we assume Poisson generated traffic and small buffer sizes for all nodes, no hidden nodes, while for the contention-based case the following assumptions have been made: $BE = 1$ and $MaxBE = 7$. In Fig. 7, the normalized throughput is plotted as a function of the generated packets for three cases, i) contention-based access ii) contention-free access, and iii) hybrid access. In this figure it is illustrated that for low traffic conditions, the contention-based and the contention-free protocols provide similar performances and hence there is no sense to employ the contention-free access scheme, since it may add overhead to the system. On the other hand, as the traffic increases the performance difference between the two protocols increases and thus clear benefits of contention-free access are arising. In this context, the hybrid approach, using the proposed criterion for mode switching, stays as much as possible in the contention-based access, i.e., until the throughput performance loss exceeds 10%, and after that threshold point is exceeded, a contention-free period is initiated for the devices. It is noted that in the same figure and for comparison purposes, the corresponding average delay (in slots) for each access scheme is also depicted.

## V. Conclusions

In this paper we investigated the access problems that arise when a number of low-complexity energy-constrained sensors simultaneously forward their data to a sink node. In order to gain insight into the problem, we first proposed a theoretical analysis, based on queueing theory, for evaluating the performance of contention-based and contention-free MAC mechanisms in terms of throughput and packet loss probability. Capitalizing on the results of this analytical approach we presented a novel hybrid protocol, which decides on the MAC protocol to be used, based on the trade-off between the expected throughput and protocol complexity. It was shown that the more efficient solution would be to utilize a contention-based MAC as the default access scheme, unless the performance in terms of throughput fails below a predetermined value. System simulation results validate the theoretical derivations and the ability of the proposed hybrid MAC scheme to balance between performance and complexity.

## VI. Acknowledgements

This work has been performed in the framework of the ICT project ICT-5-258512 EXALTED, which is partly funded by the European Union. The authors would like to acknowledge the contributions of their colleagues. This information reflects the consortiums view, the Community is not liable for any use that may be made of any of the information contained therein. This work is also co-funded by the European Union and national resources under the National Strategic Reference Framework (NSRF) and the THALES research project: ENDECON.

## References

[1] M. A. Yigitel, O. D. Incel, and C. Ersoy, "Qos-aware MAC protocols for wireless sensor networks: A survey," *Computer Networks*, vol. 55, no. 8, pp. 1982 –2004, Jun. 2011.

[2] W. Ye, J. Heidemann, and D. Estrin, "An energy-efficient mac protocol for wireless sensor networks," in *In Proc. of IEEE INFOCOM 2002*, Jun. 2002.

[3] T. Dam and K. Langendoen, "An adaptive energy-efficient mac protocol for wireless sensor networks," in *In Proc. of 1st ACM Conference on Embedded Networked Sensor Systems (SenSys 2003)*, Nov. 2003.

[4] J. Polastre, J. Hill, and D. Culler, "Versatile low power media access for wireless sensor networks," in *In Proc. of 2nd ACM Conference on Embedded Networked Sensor Systems (SenSys 2004)*, Nov. 2004.

[5] A. Barroso, U. Roedig, and C. Sreenan, "$\mu$-mac: an energy efficient medium access control for wireless sensor networks," in *In Proc. of European Workshop on Wireless Sensor Networks*, 2005.

[6] V. Rajendran, K. Obraczka, and J. Garcia-Luna-Aceves, "Energy-efficient, collision-free medium access control for wireless sensor networks," in *In Proc. of 1st ACM Conference on Embedded Networked Sensor Systems (SenSys2003)*, Nov. 2003.

[7] I. Rhee, A. Warrier, M. Aia, and J. Min, "ZMAC: a hybrid MAC for wireless sensor networks," in *In Proc. of 3rd ACM Conference on Embedded Networked Sensor Systems (SenSys 2005)*, Nov. 2005.

[8] G.-S. Ahn, E. Miluzzo, A. Campbell, S. Hong, and F. Cuomo, "Funneling-mac: A localized, sink-oriented mac for boosting fidelity in sensor networks," in *In Proc. 4th Acm Conference On Embedded Networked Sensor Systems*, Nov. 2006.

[9] A. Ouni, H. Rivano, and F. Valois, "Joint TDMA/CSMA scheduling for solving the bottleneck issue in wireless mesh networks," in *Technical Report, Institut National de Recherche en Informatique et en Automatique*, Oct. 2010.

[10] M. H. S. Gilani, I. Sarrafi, and M. Abbaspour, "An adaptive CSMA/TDMA hybrid mac for energy and throughput improvement of wireless sensor networks," *Ad Hoc Networks*, 2011.

[11] P. . IEEE Standard 802.15.4, "Wireless medium access control and physical layer specification for low rate wireless personal area networks," in *IEEE Std. 802.15.4*, 2006.

[12] M. Rusli, R. Harris, and A. Punchihewa, "Markov chain-based analytical model of opportunistic routing protocol for wireless sensor networks," in *TENCON 2010 - 2010 IEEE Region 10 Conference*, Nov. 2010, pp. 257 –262.

[13] M. Martalò, S. Busanelli, and G. Ferrari, "Markov chain-based performance analysis of multihop ieee 802.15.4 wireless networks," *Performance Evaluation*, vol. 66, no. 12, pp. 722 – 741, 2009.

[14] D. Morato, J. Aracil, J. Fernandez-Palacios, O. de Dios, and J.-F. Poyo, "On capacity planning for the gmpls network control plane," *Photonic Network Communications*, vol. 15, pp. 159–169, 2008.

[15] G. Bianchi, "Performance analysis of the ieee 802.11 distributed coordination function," *Selected Areas in Communications, IEEE Journal on*, vol. 18, no. 3, pp. 535 –547, Mar. 2000.