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On Simulation based WSN Multi-Parametric Performance Analysis

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***Abstract*—**Optimum communication and performance in Wireless Sensor Networks, constitute multi-facet challenges due to the specific networking characteristics as well as the scarce resource availability. Furthermore, it is becoming increasingly apparent that isolated layer based approaches often do not meet the demands posed by WSNs applications due to omission of critical inter-layer interactions and dependencies. As a counterpart, cross-layer is receiving high interest aiming to exploit these interactions and increase network performance. However, in order to clearly identify existing dependencies, comprehensive performance studies are required evaluating the effect of different critical network parameters on system level performance and behavior.This paper's main objective is to address the need for multi-parametric performance evaluations considering critical network parameters using a well known network simulator, offering useful and practical conclusions and guidelines. The results reveal strong dependencies among considered parameters which can be utilized by and drive future research efforts, towards designing and implementing highly efficient protocols and architectures.

***Keywords*—**Wireless sensor network, Communication Systems, cross-layer architectures, simulation based performance evaluation

I. Introduction

WIRELESS sensor networks (WSNs) constitute a rapidly evolving research area attracting high interest both by industrial and academic societies. Due to the attractive characteristics introduced such as autonomous operation, rapid and easy deployment, low cost infrastructure etc. as well as following the ad-hoc communication paradigm WSNs are able to address a wide range of application scenarios much more efficiently that other existing wireless communication technologies. Such areas include medical services, disaster relief operations, monitoring of hard to reach areas, surveillance, flora and fauna monitoring and many more.However, in order to meet the high demands posed by the aforementioned applications many challenging issues are yet to be tackled. A typical WSN comprises by tens, hundreds or even thousands of low cost and small wirelessly communicating devices. At the same time such devices are of very low capabilities and thus the available resources are quite scarce with respect to all performance aspects such as processing power, storage capabilities, communication range and last but not least energy availability. Nevertheless, these nodes are expected to perform a wide range of complex operations for days, months or even years considering various application scenarios.

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Such operations range from sensing a wide range of events and phenomena, processing and storing data, to transferring data using efficient communication protocols utilizing multi-hop communication networks.

In order for WSN nodes to cope with such high demands a whole new range of protocols and approaches are required enabling optimal resource utilization. A critical conclusion drawn from many relative research efforts is that the layered approach, based on the well known OSI/ISO model, is incapable to fulfill the optimization goals and provide the required boost in performance and resource utilization. The main reason for this inefficiency of the OSI model is the inability to take into consideration critical inter-layer interactions and respective dependencies. Aforementioned inefficiencies are cause by various observed characteristics. On one hand, in WSN many optimization objectives must be tackled concurrently in multiple layers in order to produce significant effect regarding system level performance enhancement. On the other hand many objectives are orthogonal with respect to the layer they are tackled. For example, following the minimum hop count route indicated by popular routing layer optimization approaches increases the probability of congestion and power depletion of specific nodes faced in MAC layer. Even more, it is observed that due to the limited available resources, functionalities typically implemented in specific layers are much more efficient when performed in other layers.

In order to take these dependencies in to consideration and, when possible, exploit them towards higher performance and behavior enhancement, researchers are more and more following the cross-layer paradigm. According to this concept communication stack layers are not considered in isolation but in conjunction following three main approaches. Firstly, control information is directly exchanged among layers in order to increase efficiency of one or multiple layers. Secondly information is gathered by entities outside the strict limits of the OSI model (i.e. a middleware) and following a specific process this entity is able to influence the operation of other layers. Finally specific functionalities are implemented in layers they don't usually belong, i.e. MAC layer making routing decisions or network layer affecting the duty cycle parameter of the node.However, although various efforts have been presented during the last few years, there is still a significant lack of comprehensive and holistic performance evaluation focusing on WSN networking parameters and specialized protocols. Such efforts are necessary in order to reveal the qualitative as well as quantitative characteristics of the aforementioned dependencies and interactions and thus effectively drive the design and implementation of suitable cross-layer architectures able to achieve maximum effect. Aiming to contribute to the coverage of this need this paper presents such an evaluation effort considering critical parameters in various network stack layers.Another important parameter that characterizes relative efforts concerns the means by which the evaluation is conducted. Three main methodologies are indicated in all relative network performance evaluations: utilization of analytical models, experimental test-beds and appropriate simulation platforms. Due to the high complexity of even small WSN network scenarios, the wide range of possible interactions that must be considered and consequently the inaccurate assumption that are made, analytical models are often not suitable for system level evaluation resulting to dubious results. In fact analytical models are proven most appropriate in specific functionality representations and respective studies. Furthermore, efforts relying on experimentation also suffer from significant disadvantages. Once again building a large scale fully controllable environment is very difficult if not impossible. Furthermore, caring out high number of experiments in order to provide a comprehensive evaluation considering all unforeseen and uncontrolled communication as well as natural interventions is also very cumbersome resulting in unreliable and even erroneous results and conclusions. On the other hand, system level simulation platforms are receiving active interest from the research community resulting into the development of accurate and reliable models regarding a wide range of WSN protocols and frameworks. Additionally, characteristics such as increased degree of flexibility, network parameter configuration, repeatability, and detailed measuring of any performance metric constitute the use of simulation platform the ideal choice for system level comprehensive evaluation. In this area Omnet++ 4.1 in collaboration with the MiXiM framework is one of the most well known and widely utilized platforms offering a considerable variety of accurate WSN models in combination with a flexible graphical interface and giving accurate and versatile measurements.This paper is organized as follows: in Section 2 related work is indicated and correlated to this paper. Then, Section 3 presents the main performance parameters and configurations focusing on considered protocols and their specific characteristics while Section 4 analytically presents respective measurements. Finally Section 5 discusses the main conclusions as well as possible future directions of the work presented in this paper.

II.RELATED WORK

Various research efforts have been presented in last few years shearing relative objectives with this paper. However, it is clear that the issue of cross layer interaction comprehension is still not adequately covered. Thus the work presented here aims to extend, complement and therefore lead to more valuable cross-layer multi-parametric conclusions. Research effort presented in [1] shares a similar goal however it does not consider critical aspects regarding application and physical layer. Additionally, simulation cases in [1] are extended, thus offering a more comprehensive evaluation. Another effort this work can relate to is presented in [2] where performance evaluation is attempted focusing solely on routing. Furthermore, considered routing protocols are not specifically designed for WSN networks, as well as critical performance aspects considering WSNs related to energy consumption are not taken into consideration. Even more, MAC layer, being of cornerstone importance in WSN performance, is also omitted, and following the experimentation approach the considered simulation scenarios are of low complexity regarding both topologies and varying parameters. Work in [3] also aims to offer a WSN performance evaluation, although protocols considered are not well suited for WSN networks and measurements focus solely on routing efficiency and good-put, thus omitting significant aspects such as energy conservation. Another interesting evaluation is presented in [4] focusing on a specific application case considering one mobile sink and energy related measurements. However, as in other related efforts, protocols considered derive from the MANET network area and thus probably comprise suboptimal choices with respect to a WSN environment. Routing development aiming towards lifetime extension as presented in [5] is also an area that work presented in this paper can significantly assist and extend. Without a doubt physical layer and respective peculiarities are of cornerstone importance in WSN performance. In that respect efforts presented in [6-8] focus on this layer offering valuable results concerning experimental evaluation of physical layer in forest environment, a survey of physical layer oriented simulators and a study on the complexity and accuracy of respective simulation modes respectively.

III. SIMULATION PARAMETERS AND CONFIGURATION

Significant effort is devoted in porting suitable and adequate WSN protocols model into the Omnet++ MiXiM modeling framework. Medium access control and routing represent the most important parameters of a network as far as its behavior and performance is concerned. Consequently, in order to perform an objective analysis and expose significant cross-layer characteristics, careful consideration is made upon the respective selections. Focusing on MAC layer approach, the two main techniques utilized are contention and contention-free access, thus a well known representative from each technique is considered. BMAC is probably the most widely utilized contention-based WSN MAC protocol. Medium access and channel arbitration is based on a preamble transmitting mechanism enabling channel reservation, when idle, and tackling the issue of reception of a packet by a node residing in sleep state when transmission commences. Aiming towards lightweight and low complexity implementation, BMAC does not incorporate control functionality such as RTS/CTS control packets. On the other hand due to its duty cycle operation significant energy conservation is possible while facilitating a wide range of WSN applications [9]. On the other hand, LMAC is also a well known WSN MAC protocol following the schedule-based, contention-free paradigm. Based on ideas introduced by the EYES IST project [10] aims to efficiently time-schedule all communicating nodes of a WSN following a completely distributed procedure [11]. Each node relies on local connectivity information in order to select suitable time-slots that will assure collision free transmission with respect to nodes in its broadcast domain. At the same time, awareness of each slot's owner enables each node to maximize the time period it can turn off its radio, thus facilitating energy consumption minimization. As for the routing functionality of the network layer, the well-established Directed Diffusion protocol [12] is considered. It is based on a subscriber-based system, thus the sinks send interest messages periodically to inform the other nodes of their particular needs. These packets disseminate throughout the network, establishing gradients that point to the message originators. Exploiting the one-phase pull mode of the Directed Diffusion, there is only one phase for the establishment of gradients. In particular, each node determines its preferred gradient by the neighbor who was the first to send the matching interest, thus suggesting a low latency path. This protocol assumes symmetric communication between nodes since the data path (source-to-sink) is determined by lowest latency in the interest path (sink-to-source). In fact this requirement poses no threat because this is the case in our simulation configuration. In our evaluation we considered specific parameters of the routing protocol such as the interest flooding period.

A. Simulation Configuration

In this section the main simulation configuration parameters are presented in order to achieve the evaluation's objectives. Topologically, in order to assure a controllable environment a grid topology is considered formed by sixteen nodes placed appropriately so as each node is able to communicate only with its immediate neighbors as indicated in Figure 1. As far as data flow related parameters are concerned two critical aspects are exploited. Firstly, considering that the number of concurrent data flows significantly affect the competition for the medium access three respective cases are taken into consideration as indicated in Table 1. Furthermore, it is important to note that, for each number-of-data-flows case, five different, randomly selected scenarios are considered regarding the data packet creating nodes thus, considering all possible number of hop cases and further enhancing the validity of the acquired measurements and respective extracted conclusions. Secondly, the actual workload that each flow imposes significantly affects network behavior thus a wide range of relative values is considered (Table 1) enabling network evaluation under diverse cases varying from light to excessive workload. Another critical issue concerns the configured duty cycle, which expresses the time duration percentage a node ideally remains active, thus essentially representing the goal as far as energy conservation is concerned. The importance of this parameter is augmented by the fundamentally different approach each considered MAC protocol uses to arbitrate medium access. Specifically, BMAC follows a straightforward approach enabling the specification of the active time duration percentage assuming that no traffic is to be handled (either transmission or reception). In contrast in LMAC, which follows a time division based concept, each node is configured as owner of a timeslot of predefined time duration. This effectively, in case of light traffic determines the period each node samples the transmission medium which is, therefore, equivalent to duty cycle BMAC configuration. In that respect Table 1 depicts the duty cycle percentage configuration for BMAC and LMAC respectively. Another important note concerns the LMAC minimum slot duration which is estimated approximately twice compared to BMAC since it must be able to facilitate two control messages whereas in BMAC is equal to Clear Channel Assessment (CCA) duration. For the analysis purposes CCA for BMAC is considered 10msec, which is a realistic duration, based on existing platforms. Focusing on routing layer, routing update period is probably the most critical parameter. This parameter represents an important trade-off between quick response to topology changes and control data overhead imposed by respective routing packets.

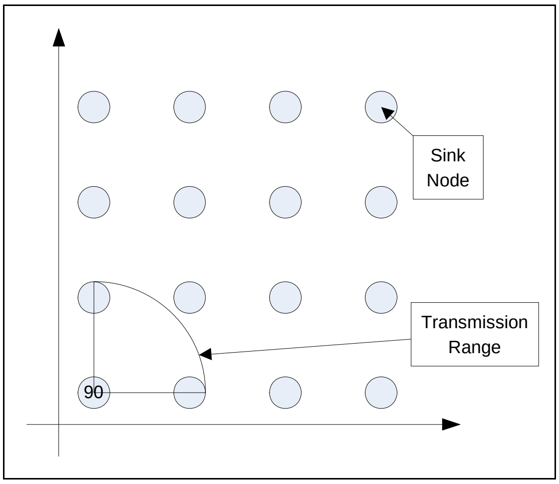

Fig. 1 Network Topology

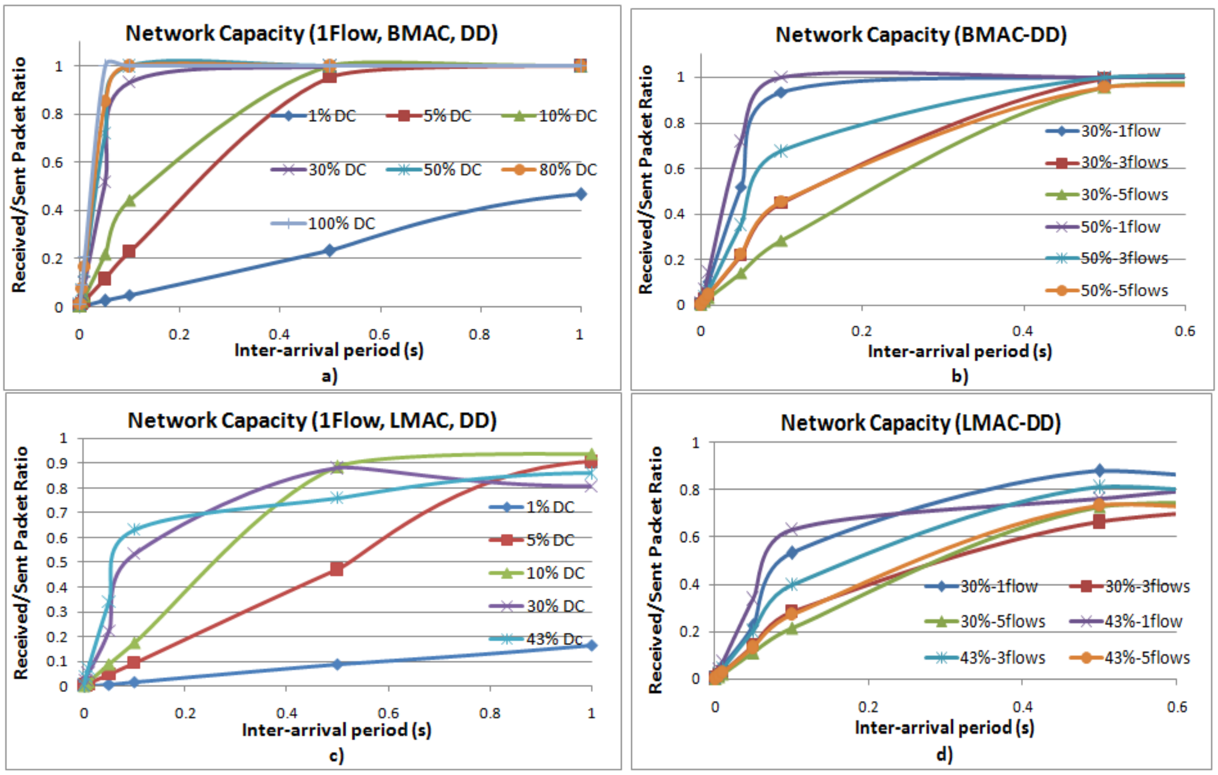

Figure 2: Successful Transmission Measuremetns Excluding Routing Protocol Overhead

Last but not least, all simulations are performed using the Omnet++ 4.1 discrete event simulator utilizing the MiXiM-framework, where all required protocols are ported, and each simulation is repeated at least 10 times alternating the seed of random generators utilized. Thus, considering mean values further increases the reliability of extracted measurements and conclusions.The previous critical parameters as well as all main common parameters are depicted in Table 1.

TABLE I
SIMULATION PARAMETERS

Simulation Parameter	Values
MAC Protocols	BMAC, LMAC
Routing Protocol	Direct Diffusion
Concurrent Data Flows	1, 3, 5 (5 Different traffic generating nodes cases)
Packet Inter-arrival period	10, 5, 1, 0.5, 0.1, 0.05, 0.01, 0.005, 0.001
BMAC Duty Cycle Conf. %	1, 5, 10, 30, 50, 80, 100
LMAC Duty Cycle Conf. %	1, 5, 10, 30, 43
Routing update period (sec)	1, 5, 20, 40, 160
Packet size (byte)	77
Transmission rate (kbps)	200
MAC Queue length	2 packets
Single simulation repetition	>10

At this point it is important to elaborate on the distinction between configured and measured effective duty cycle considerate in this paper, which to the best of our knowledge it is not considered in other related efforts. On one hand, both MAC protocols (although following a different approach) aim towards power conservation by turning off the radio for as long as possible while at the same time try to minimize the loss of data or packet delay increase due to that operation. On the other hand, however, the actual time period the node will be able to remain in a powered off state depends strongly on the communication conditions existing in the network regarding traffic workload, paths selected by the routing protocols, concurrent data flows, number of hops and various other parameters. Therefore, configured DC in the following evaluation corresponds to what the network ideally aims to, while effective DC comprises a critical network performance parameter measured, corresponding to the actual time period a node remains in sleep state thus indicating the degree of power conservation one can anticipate. The other two, widely used, network performance parameters considered are capacity related and packet delay measurements. Related to the former parameter the successfully received packet to the number of transmitted packets is considered depicting the capabilities of the network to convey data packets with respect to the specific network parameters of each simulation. At the same it represents the mean throughput of the network for the simulation duration. Focusing on the latter parameter, packet delay is measured at application layer thus taking into consideration the effect of all layers, and the respective parameters. Of course, the value presented is the mean value of all delay measurements for each simulation.

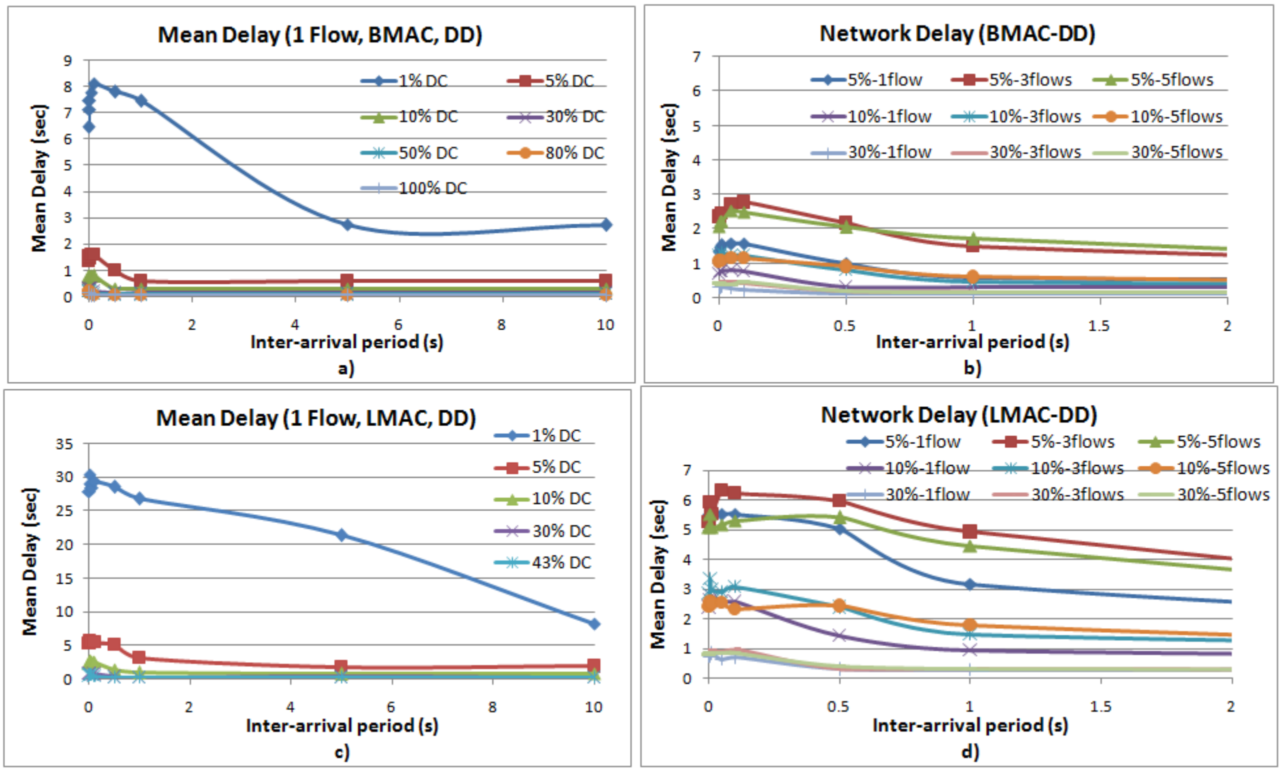

Fig. 3 Mean Packet Delay Measuremetns Excluding Routing Protocol Overhead

IV. Performance Evaluation

In order to facilitate the evaluation process, as well as offer useful and the objective evaluation presentation, all measurements conducted are divided into two sub-sections. The fist one excludes the effect of routing protocol as it is expected to apply in a stable and robust network scenario. In this way all other parameters are studied in great detail offering the first level of analysis. Driven by the aforementioned analysis and based on respective conclusions, in the second section the effect of routing protocol overhead on network performance in specifically analyzed based on considerably more focused measurements.

A. Analysis Excluding Routing Overhead

In such scenarios, measurements are considered after the end-to-end data path is discovered while the update period is fairly long, thus the importance of routing protocol overhead is effectively diminished. For reasons of completeness it is mentioned that respective performance evaluations concern direct diffusion routing protocol although main conclusions can be extended to other routing protocols as well. Routing update period for this section is configured to 160 seconds thus minimizing respective effect.

1) Network Throughput Capabilities Measurements

With the network bandwidth demands continuously increasing, one of the important network parameters concerns the amount of data the network can handle successfully. Respective measurements are depicted in Figure 2, presenting received to transmitted data ratio with respect to all critical network parameters considered and focusing on 0 to 1 sec inter-arrival period where the most significant conclusions are extracted. The first significant observation concerns the profound effect configured DC has on capacity measurements with respect to imposed workload. To exclude the effect of multiple concurrent data flows analysis focuses on Figure 2a and c. When BMAC and 1% configured DC is considered the packet receive ratio is only 50% even for 1 sec packet period and is diminishing very rapidly, thus discouraging the use of such configuration in most application scenarios. Increasing the configuration of DC to 5% substantially enhance respective network capability which approaches 80% increase for 0.5 sec inter-arrival period. Doubling DC configuration to 10% lead to only a slight ratio increase localized only at 0.1s packet period whereas no substantial difference is observed for the rest of packet inter-arrival period range thus not advocating such configuration when considering the negative effect such DC configuration represents on power conservation. Moving on, DC configurations higher than 30% also exhibit a very interesting behavior. As shown in Figure 2a respective configurations provided success receive ratio higher than 93% up to 0.1s packet interval, corresponding to 10 packet creations each second which can be considered sufficient for a wide range of WSN applications assuming that the respective significant energy cost is acceptable. Focusing on even higher workload scenarios, all cases exhibit rapid degradation. Especially considering 0.05sec packet interval, only 100% and 80% configured DC cases provide success packet reception ratio above 80%, whereas 50% configure DC drops to 70% successful packet transmissions and for 30% DC only half the packets generated are successfully received by the sink node. Lower packet intervals represent excessive traffic scenarios resulting in measurements no higher than 20% success ratio. In contrast, in LMAC based simulations different behavioral characteristics are depicted (Figure 2c) while it is apparent that the time-division approach of LMAC significantly affect the overall network performance. Once again it is quite evident that 1%DC, although it may contribute to power conservation, results in emphatic performance degradation thus discouraging the use of such low configuration. As it is anticipated 5%DC offers substantial performance improvement although the effect of packet interval is much more significant compared to BMAC based evaluation indicated by a much more rapid communication success ratio decrease and an almost linear respective graph. Another interesting behavioral characteristic concerns the performance collapse of 10%DC moving from 0.5 to 0.1sec packet interval thus leaving the 30%DC and 43%DC configurations offering higher that 50% success ratio (i.e. 53% and 63% respectively). Considering even higher traffic scenario all DC cases present significant degradation thus, compared to BMAC respective cases, a much more limited useful traffic range can be anticipated. Additionally to the relatively more robust and more efficient behavior of the BMAC in all cases, trying to quantify this advantage one can extract that BMAC offers a performance increase varying from ~10% up to approximately 45% as opposed to LMAC.The effect of increasing concurrent data flows is shown in Figure 2b and d, and is substantially differentiated with respect to the MAC protocol utilized. As far as BMAC is concerned Figure 2b indicates that up to 0.5sec packet interval the effect of multiple data flows can be considered negligible, thus imposed contention can be efficiently handled. However, for lower inter-arrival period the effect becomes abruptly evident, which is justified by the contention based approach of BMAC and clearly indicated for 0.5sec packet interval. It must be noted that moving from 1 to 3 flows has a more pronounced effect (i.e. performance decrease) than when moving from 3 to 5 concurrent data flows. This is justified by the BMAC theoretical analysis, since in the former case contention appears among the concurrent data flows, which is the critical issue here, whereas in latter already existing competition among flows is further augmented. On the other hand, LMAC due to its time-division characteristic exhibits a more predictable and steady behavioral effect of the concurrent data flows. As indicated the effect is apparent prior to 0.5sec packet interval and relative packet transmission success ratio differences present a similar pattern in all cases up to 0.05s. Higher traffic rates represent excessive workload scenarios which may lead to misleading conclusions.

2) Network Delay Capabilities Measurements

In this section the cross-layer effect of considered parameters on delay performance is analyzed as indicated in Figure 3 presenting respective measurements. Following the same analysis paradigm as in previous section, firstly 1-flow measurements are presented (Figure3a and c) thus eliminating the contention factor and narrowing down the ranges of considered parameters, thus providing useful and practical observations. Therefore, the most evident observation, as with capacity related measurements, concerns 1% configured DC poor performance for the whole traffic rate range and especially for medium to high workload (packet inter-arrival period lower than 2sec). Based on this performance as well as compared to 5%DC performance respective configuration does not offer any significant advantage. This is even more emphatic in LMAC based scenarios where even for 5sec packet inter-arrival period (i.e. very low workload) respective measurements are above 20sec. Moving on to 5%DC delay performance is substantially enhanced even though the delay penalty compared to the rest of DC configuration is considerable. The last worth noting remark extracted from the 1-flow graphs concerns the fact that DC configurations of value from 30% and higher do not impose any noticeable delay variation. Respective measurements are stable for the whole workload range and below 0.5sec for BMAC and 1sec for LMAC, making them equally appropriate choice as far as delay is concerned, able to provide a significantly stable and efficient network performance and thus meeting the demands of a wide range of respective realistic applications.Focusing on Figure 3b) and d) a comparative analysis can be extracted concerning the effect of different MAC protocols as well as the effect of concurrent data flows representing contention. To provide a more practical analysis DC configurations presented are limited to 5%, 10% and 30% while the packet inter-arrival period limited from 0 to 2 sec thus offering a significantly more detailed representation. As it is clearly depicted LMAC utilization leads to significantly higher mean packet delays and usually approximately doubling respective BMAC measurements. Such characteristics can be attributed to the unavoidable delay between consequent slots owned by the same station, since slots of all other neighboring nodes must intervene. Another, very interesting conclusion is that the effect of concurrent data flows, although measurable, is not very significant indicated by the fact that all graphs concerning different number of data flows for the same DC configurations are tightly grouped together and can be distinctly separated from the rest of DC configurations. Specifically in both cases 5% configured DC graphs produce the higher delays, followed by the 10% DC graphs and finally followed by 30% DC graphs where it is noted that the effect of multiple data flows can be considered negligible. A secondary comment concerns the anticipated behavior where delay effect increase concurrent data flows from 1 to 3 is slightly higher than moving from 3 to 5 in most cases.

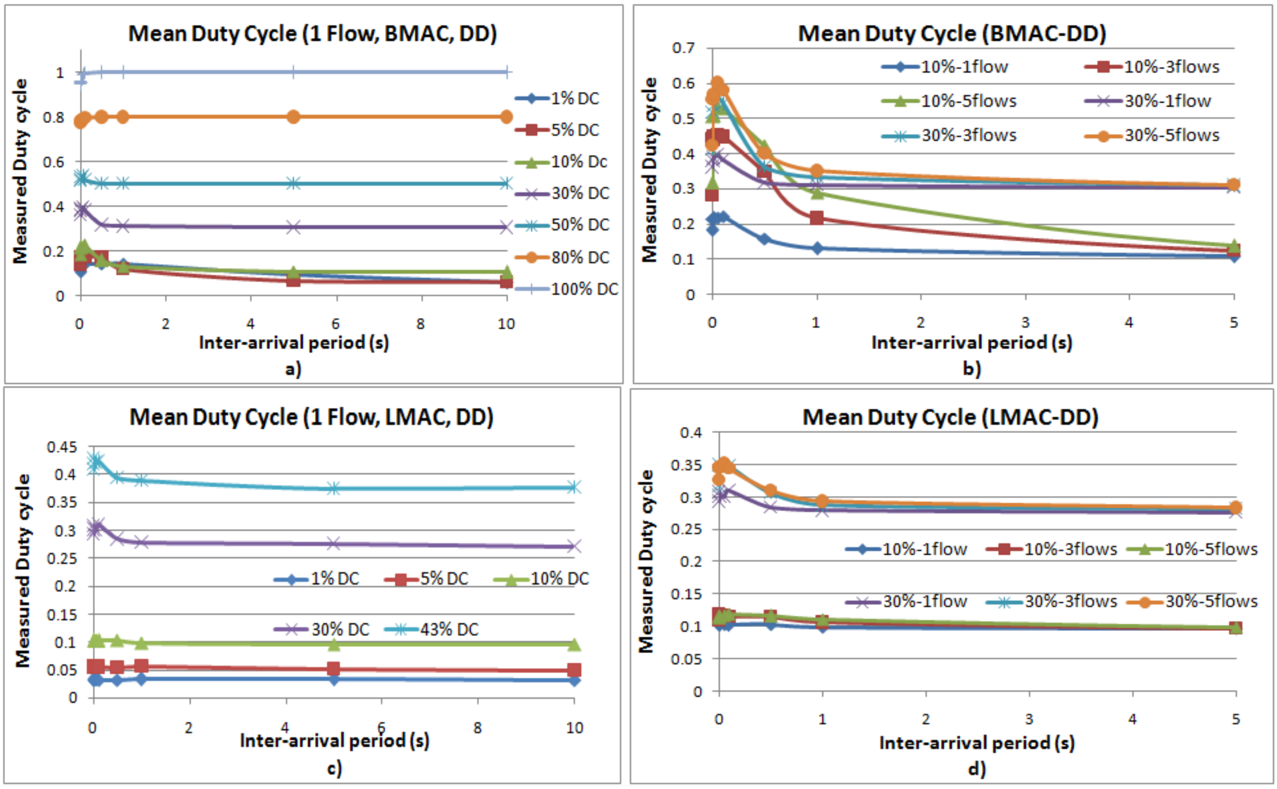

Fig. 4 Effective Duty Cycle Measuremetns Excluding Routing Protocol Overhead

3) Energy Conservation Capabilities Measurements

Power conservation comprises one of the cornerstones of efficient sensor network architecture. Therefore, it is critical to identify and expose respective cross-layer characteristics. The most objective measurements to base such analysis is the effective duty cycle, that is the time period a node is actually able to remain in sleep state aiming to minimize radio power consumption which constitute the main source of energy expenditure. As far as 1-flow scenarios are concerned, as depicted in Figure 4a) and c), conclusions are quite straightforward since effective DC remains relatively unaffected by the traffic rate imposed. Therefore, when a single flow is anticipated to occupy the transmission medium the expected power conservation aimed by the configured DC will be actually delivered in system level. Focusing on BMAC it is noted that the only cases where effective DC is increased compared to configured DC is for low configured DC and significantly high traffic. This is anticipated since in these cases nodes have more traffic to handle and there is availability for DC increase as opposed to cases with configured DC over 50% where the active time period is by configuration high enough and no more increase can actually help. On the contrary the time division approach of LMAC is again evident in these measurements indicated by the completely steady behavior of the graphs.

The different approaches followed by MAC protocols have a much more profound effect on duty cycle measurements when analyzed with respect to concurrent data flows (Figure 4 b and c). As observed when BMAC is used contention lead to a significant increase of duty cycle especially in low DC configuration cases where higher power conservation is expected. Specifically, considering 10% configured DC and 3 concurrent data flows, effective DC is equal to 20% for 1sec packet interval (representing a 100% increase) period which approaches 30% representing a substantial increase of more than three times higher active periods than configured. Analogous increase is recorded for 30% configured DC although of considerably lower degree. In worst case scenarios measured DC reached approximately 60% doubling the configured active time period. Furthermore, in many cases effective duty cycles measurements over 40% and 50% are recorded which must be taken under serious consideration depending upon the application requirements in conjunction with performance in the other performance metrics analyzed earlier. On the other hand, it is of critical importance to notice that once again LMAC offers a much more stable and predictable behavior since increasing the number of concurrent data flows result in negligible effect on measured DC. Therefore, it is clear that LMAC is able to provide the anticipated power conservation under a wider range of workloads and critical parameter offering a more predictable and steady network operation.

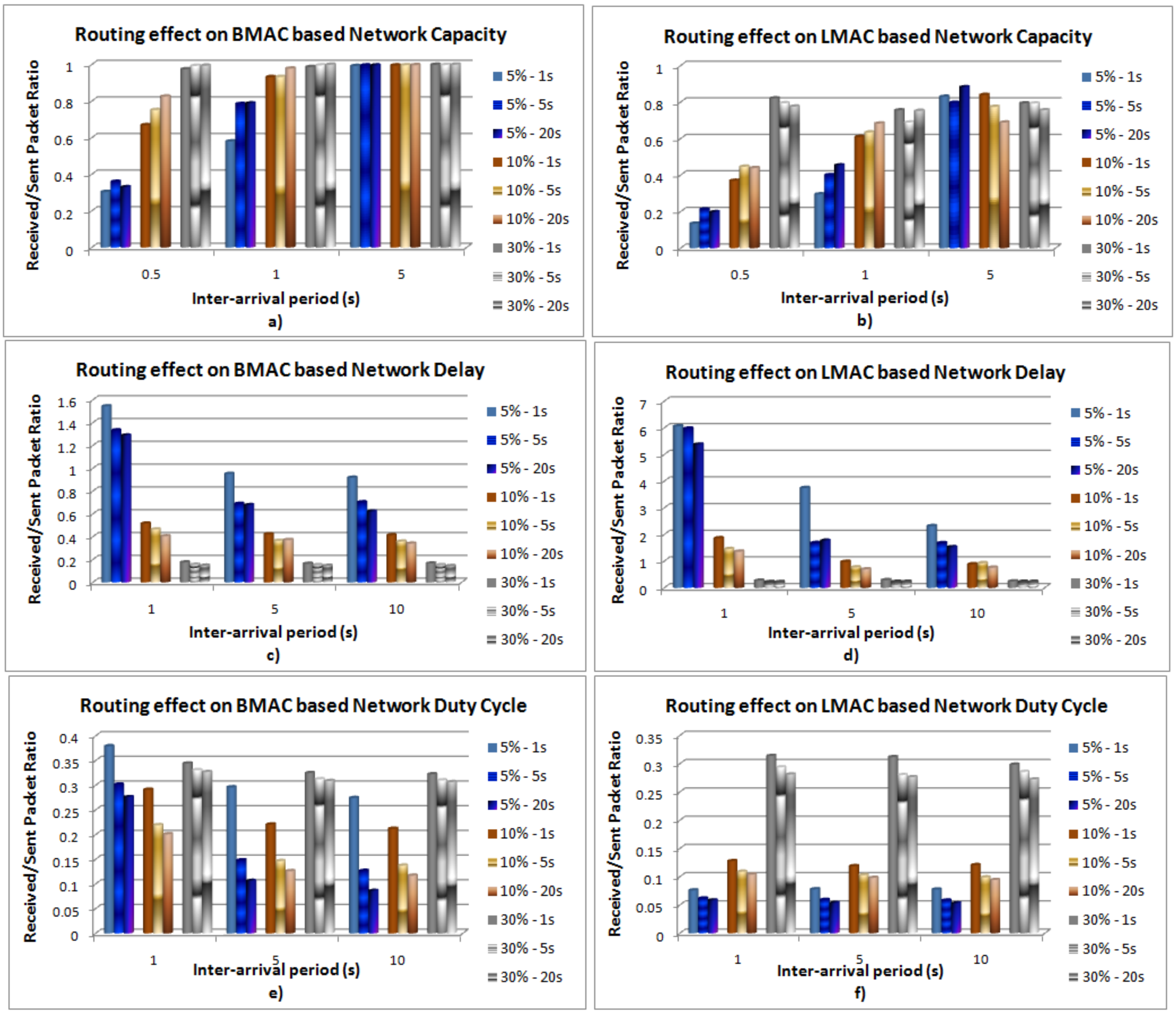

Fig. 5 The Routing Overhead Effect on Delay and Effective DC Performance

B. *The effect of routing overhead*

In the previous section, scenarios considered a stable, robust network where routing protocol, following the discovery of the path, effectively did not impose any significant overhead. However, in mobile or unstable network scenarios routing protocol must update the discovered path rapidly (depending of the anticipated rate of topology changes) in order to assure node connectivity. Therefore, in these particular cases routing imposes an important tradeoff between performance overhead and rapid routing path updates. In order to evaluate this tradeoff simulation measurements are carried out considering 3 concurrent data flows, the three most prominent DC configurations and three routing packet periods able to present critical trade-offs (i.e. 1, 5 and 20 seconds period, ranging from rapid to relatively slow routing update procedure). Respective measurements are presented in Figure 5 where it is noted that each graph corresponds to measurements considering two parameters. The first on (expressed in percentage) concerns the configured DC and the second (expressed in seconds) concerns the routing update period.Regarding capacity related effect of routing overhead, Figure 5a) and b) depict respective measurements. Besides the overall enhanced performance of BMAC compared to LMAC, the new significant observation concerns the fact that routing overhead can indeed affect capacity performance, especially when combined with high traffic rates. Therefore, and focusing on BMAC it is shown that, although when low traffic is considered, no effect is indicated by increased routing overhead, for medium and high traffic the effect becomes quite apparent. Specifically when reducing the routing update period from 20 to 1 seconds a respective capacity reduction can reach up to 20%. One the other hand, LMAC's schedule based approach diminishes the respective parameter effect since the maximum capacity performance degradation measured may reach approximately 15%. At the same time the average performance deviation due to routing overhead is considerably less significant compared to BMAC measurements. Furthermore, another worth noting observation concerns specific cases (i.e. 5sec inter-arrival period and 10% configured DC) where LMAC's performance is actually enhanced by increasing the routing updates frequency. Such behavior, although counter intuitive, indicates that frequent routing updates can potentially lead to more efficient path establishment which facilitates time scheduled based transmission medium access approaches.Figure 5c) and d) indicate the delay effect of direct diffusions routing overhead with respect to MAC protocols, configured DC, routing updates and packet inter-arrival periods. As it is depicted in all cases reducing routing update period up to 5sec imposes either a negligible or moderate, thus acceptable, delay increase. The same conclusions can be extracted considering 30% and 10% DC configurations. However, 1sec routing update period lead a considerable and in some cases quite substantial delay increase when nodes operate at 5% configured DC. In particular, considering LMAC utilization, reducing routing period from 5 to 1sec can lead to a delay increase varying from 50% up to more than 100% (in 10 and 5sec packet inter-arrival period respectively). Analogous observations in BMAC case also indicate significant delay increase reaching 50% in medium workload scenarios. Overall LMAC seams more susceptible to delay increase due to routing overhead, which is attributed to the fact that when a slot is utilized for routing packet transmission, data packet must wait for slow sequence until the next slot owned by the same station, in contrast to BMAC where the node is not restrained to compete for medium access continuously. However, the time division nature of LMAC that leads to a less efficient delay behavior to routing overhead is the reason that LMAC exhibits a much more stable and predictable behavior as far as effective DC is concerned. Respective measurements are presented in Figures 5e) and f). From these figures, it is evident that increasing the routing updates frequency leads to a profound effect on measured DC when BMAC is considered. Thus, focusing on Figure 5c and particular in medium and low workload cases (where the effect can be attributed almost entirely to routing protocol) reducing routing update period from 5 to 1 sec lead to an approximately 50% or even 100% effective DC increase, for 10% and 5% configured DC respectively. Therefore, such behavior is expected to lead to a respectively significant increase as far as network energy consumption is concerned. On the other hand LMAC seems to be much more immune to routing protocol update frequency. This is indicated by the fact that increasing the routing update frequency had a moderate effect of measured DC (~10%) independent to the configured DC or workload.

V. Conclusions

The main objective of this paper is to address the need for detailed cross-layer multi-parametric performance analysis of WSN networks. Such studies are of critical importance when aiming to design advanced network architectures and techniques able to enhance network performance in various aspects such as capacity, end to end packet delay and power conservation.Therefore, an extensive performance and behavioral evaluation is conducted and presented considering critical network parameters in various network layers such as application, routing and MAC. Respective measurements revealed and exposed important dependencies among the different parameters as well as cross-layer characteristics. The aforementioned dependencies and interactions are analyzed both quantitatively and qualitatively leading to objective, useful and practical conclusions.As future work the derived conclusions and guidelines will drive the design, implementation and validation of advanced techniques and network designs towards further boost of performance and optimal resource utilization.

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