Area Throughput for CSMA Based Wireless Sensor Networks

(Invited Paper)

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Abstract—In this paper we present a mathematical approach to evaluate the Area Throughput of a multi-sink Wireless Sensor Network (WSN), where nodes transmit their packets to a sink, selected among many. Sensors and sinks are both Poisson distributed in a bounded domain. A Carrier Sensing Multiple Access (CSMA) based protocol is used by nodes to access the channel. We denote as Area Throughput the amount of samples per second successfully transmitted to the sinks. This performance metric is strictly related to both connectivity and MAC issues: it depends, in fact, on the probability that a given sensor node is not isolated and that it succeeds in transmitting its packet (i.e., the packet does not collide). The aim of this work is to devise a mathematical model that takes CSMA and connectivity issues into account under a joint approach. Through this model some network optimisation strategies could be derived. As an example, sensors could perform an aggregation procedure, responding sporadically to queries with a single packet composed of all samples taken since the previous transmission. Our model allows the evaluation of the optimum size of the packet that should be transmitted, so that the Area Throughput is maximised. Finally, the effects of the connectivity on the Area Throughput are evaluated.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) [1] are about collecting data from the environment through the sampling of some physical entities (like temperature, humidity, etc), and sending them to a user, usually through some infrastructure networks such as the Internet, or a mobile radio system (e.g. GPRS, UMTS). Applications of WSNs can be split into two major categories, namely event-triggered sampling and spatial/temporal process estimation [2]. In the latter case, the environment is observed through queries/respontend mechanisms: queries are periodically generated by the user, and sensor nodes respond by sampling and sending data. The user, by collecting samples taken from different locations, and observing their temporal variations, can estimate the realisation of the observed process [3]. Good estimates require sufficient data taken from the environment.

If few sensor nodes are deployed over a small area, a single network coordinator (denoted as sink in the following) can be used as collector of the data sampled, and as gateway towards the infrastructure. When the number of sensor nodes is large, they are often organised in clusters, where one sink per cluster spreads the queries to the sensors, collects the responses and manages data transmissions.

Access to the radio channel is often based on random multiple access techniques [4], [5] as scheduling of transmission is usually impossible for several reasons (sleep/active node cycles, frequent change in the network topologies, etc). Carrier Sense Multiple Access (CSMA) methods are very often used for WSNs: the most widely adopted standard air interface technique is IEEE802.15.4 [6], whose two operational modes (beacon and non-beacon enabled) are based on CSMA.

Sinks are sometimes specifically designed as WSN nodes, and deployed in optimised and planned locations with respect to sensors. However, opportunistic exploitation of the presence of mobile sinks, connected to the infrastructure through some mobile radio interface is an alternative in some cases [7]. Under these circumstances, many sinks can be present in the monitored space, but their positions are unknown and unplanned.

In many applications of WSNs, the data must be taken from a specific portion of space, even if the sensor nodes are distributed over a larger area. Therefore, only a location-driven subset of sensor nodes must respond to a query. The aim of the query/response mechanism is to acquire the largest possible number of samples from the target environment, per unit of time.

However, if the sinks are randomly distributed according to the opportunistic paradigm mentioned above, achievement of a sufficient level of samples is not guaranteed, because the sensor nodes might not reach any sinks according to the limited transmission range. Therefore, in such an uncoordinated environment, network connectivity is a relevant issue, and it is basically dominated by the randomness of radio channel and the density of sinks.

On the other hand, the density of sensor nodes significantly affects the ability of the CSMA mechanisms to prevent from collisions over the air interface (i.e. simultaneous transmissions from separate sensors towards the same sink); if the number of sensor nodes per cluster is very large, collisions and backoff procedures can make data transmission impossible under time-constrained conditions, and the samples taken from sensors do not reach the sinks and, consequently, the user.

If the number of sensor nodes in the target area is too large, causing many data losses, one solution can be found in the decimation of the sensor nodes to respond. Other improve-
ments might be introduced by letting the sensor nodes apply a form of aggregation procedure, responding only sporadically to queries, with a single data packet composed of all samples taken since the previous transmission: fewer access attempts are performed, but with longer packets.

Such decimation process, or the aggregation strategy, must be driven by an optimisation procedure that, by taking into account the density of sensor nodes and sinks, the frequency of queries, and the randomness of node locations, the radio channel behaviour, and CSMA mechanisms, determines the optimum number of nodes that should respond to any query, and whether aggregating samples provides advantages.

This paper addresses such optimisation problem. We consider a large area where sensors and sinks are uniformly and randomly distributed. Then, we define a specific portion of space, of finite size and given shape, as the target environment; both the number of sensors and sinks are then Poisson distributed in such space (see Figure 1, above part). Without loss of generality, we assume the finite target area is of square shape. Denoting as Area Throughput the amount of samples per second successfully transmitted to the sinks (that we assume to be constraintless connected to the infrastructure), our aim is to devise a mathematical model that takes CSMA and connectivity issues into account under a joint approach, with particular emphasis on the IEEE802.15.4 MAC protocol in non-beacon enable mode.

Many works in the literature are related to the modelling of different CSMA based MAC protocols, and also to connectivity models, but very few papers jointly consider the two issues under a mathematical approach. Some analysis of the two issues are performed through simulations: as examples, [8] related to ad hoc networks, and [9], to WSNs. Many papers devoted their attention to connectivity issues of wireless ad hoc and sensor networks in the past (e.g., [10]). Single-sink scenarios have attracted more attention so far. However, an example of multi-sink scenario can be found in [11]. All the previously cited works do not account for MAC issues.

Concerning the analytical study of CSMA based MAC protocols, in [12] the throughput for a finite population when a persistent CSMA protocol is used, is evaluated. An analytical model of the IEEE802.11 CSMA based MAC protocol, is presented by Bianchi in [13]. In these works no physical layer or channel model characteristics are accounted for. Capture effects with CSMA in Rayleigh channels, are considered in [14], whereas [15] addresses CSMA/CA protocols. However, no connectivity issues are considered in these papers. In [16] the per-node saturated throughput of an IEEE802.11b multi-hop ad hoc network with a uniform transmission range, is evaluated.

The model proposed here is based on some previous works: [17], where the Authors presented a mathematical model for the evaluation of the degree of connectivity of a multi-sink WSN in unbounded and bounded domains; and [18], [19], where a mathematical model to derive the success probability for the transmission of a packet in an IEEE802.15.4 single-sink scenario, is provided.

The rest of the paper is organised as follows. The following Section introduces the scenario, the data aggregation strategy and the link model. In Section III the Area Throughput is evaluated, by computing the success probability for the transmission of a packet accounting for connectivity and MAC issues. In Section IV the particular case of the IEEE802.15.4 CSMA based protocol is considered, for the evaluation of the success probability related to MAC. Finally, in Section V and VI numerical results and conclusions are presented.

II. ASSUMPTIONS AND REFERENCE SCENARIO

The reference scenario considered consists of an area of finite size and given shape, where sensors and sinks are both distributed according to a homogeneous Poisson Point Process (PPP). We denote as \( \rho_s \text{ [m}^{-2}] \) and \( \rho_0 \text{ [m}^{-2}] \) the sensors and sinks densities, respectively, and with \( A \) the area of the target domain. Denoting by \( k \) the number of sensor nodes in \( A \), \( k \) is Poisson distributed with mean \( \bar{k} = \rho_s \cdot A \) and p.d.f.

\[
g_k = \frac{\bar{k}^k e^{-\bar{k}}}{k!}.
\]  

We also denote as \( I = \rho_0 \cdot A \) the average number of sinks in \( A \).

A. The Aggregation Strategy

Sinks periodically send queries to sensors and wait for replies. In case a sensor node receives a query from more than one sink, it selects the one providing the largest received power and responds to it. We assume that sensors may perform some data aggregation before transmitting their packets. For instance, they perform sampling from the environment upon each query, but transmit data only when a given number of samples have been collected. By doing so, transmissions do not occur at each query.

We denote as \( T \) the time needed to transmit a unit of data, that is one sample, and as \( T_D \) the time needed to transmit a packet. The frequency of the queries transmitted by the sinks is denoted as \( f_q = 1/T_q \). \( T_q \) is the time interval between two consecutive queries and is set to \( q \cdot T \); therefore, a finite number, \( q \), of intervals \( T \) are contained in \( T_q \). We assume
that sensors transmit packets composed of $D$ samples every $D$ queries. At each query sensors take one sample and when $D$ samples are taken, data is aggregated and transmitted. We assume that the aggregation process generates a packet whose transmission requires a time $T_D = D \cdot T$, when $D$ units of data are aggregated. In Figure 1 (below part), the aggregation strategies in the cases $D = 1, 2$ are shown as examples.

B. The Link Model

The link model that we exploit accounts for the power loss due to propagation effects including both a distance-dependent path loss and the random channel fluctuations caused by possible obstructions. Specifically, a direct radio link between two nodes is said to exist if $L < L_\text{th}$, where $L$ is the power loss and $L_\text{th}$ represents the maximum loss tolerable by the communication system. In that case, the two nodes are said to be "audible". The threshold $L_\text{th}$ depends on transmit power and receiver sensitivity. The power loss in decibel scale at distance $d$ is expressed in the following form

$$L = k_0 + k_1 \ln d + s,$$ \hspace{1cm} (2)

where $k_0$ and $k_1$ are constants, $s$ is a Gaussian r.v. with zero mean, variance $\sigma^2$, which represents channel fluctuations. This channel model was also adopted in [20]. By considering an average transmission range as in [20], an average connectivity area of the sensor can be defined as

$$A_\sigma = \pi e^{2(\ln - k_0) \over k_1} e^{2\pi^2 \over k_1}.$$ \hspace{1cm} (3)

III. EVALUATION OF THE AREA THROUGHPUT

The Area Throughput is mathematically derived through an intermediate step: we first consider the probability of successful data transmission by an arbitrary sensor node, when $k$ nodes are present in the queried area. Then, the overall Area Throughput is evaluated based on this result, given the aggregation strategy described in Section II.

A. Joint MAC/Connectivity Probability of Success

Let us consider an arbitrary sensor node that is located in the queried area $A$ at a certain time instant. We aim at computing the probability that it can connect to one of the sinks deployed in $A$ and successfully transmit its data sample to the infrastructure. Such an event is clearly related to connectivity issues (i.e., the sensor must employ an adequate transmitting power in order to reach the sink and not be isolated) and to MAC problems (i.e., the number of sensors which attempt at connecting to the same sink strongly affects the probability of successful transmission). For this reason, we define $P_{s|k}(x, y)$ as the probability of successful transmission conditioned on the overall number, $k$, of sensors present in the queried area, which also depends on the position $(x, y)$ of the sensor relative to a reference system with origin centered in $A$. This dependence is due to the well-known border effects in connectivity [10].

In particular, we assume

$$P_{s|k}(x, y) = E_x[P_{\text{MAC}}(n) \cdot P_{\text{CON}}(x, y)]$$

$$= E_x[P_{\text{MAC}}(n) \cdot P_{\text{CON}}(x, y)]$$ \hspace{1cm} (4)

where we separated the impact of connectivity and MAC on the transmission of samples. A packet will be successfully received by a sink if the sensor node is connected to at least one sink and if no MAC failures occur. We now analyze the two terms that appear in (4).

$P_{\text{CON}}(x, y)$ represents the probability that the sensor is not isolated (i.e., it receives a sufficiently strong signal from at least one sink), which is computed in [17] for a scenario analogous to the one considered here (e.g., squared and rectangular areas). This probability decreases as the sensor approaches the borders (border effects). Specifically, since the position of the sensor is in general unknown, $P_{s|k}(x, y)$ of (4) can be deconditioned as follows:

$$P_{s|k}(x, y) = E_x[P_{\text{CON}}(x, y)] \cdot E_x[P_{\text{MAC}}(n)].$$ \hspace{1cm} (5)

It is also shown in [17] that border effects are negligible when $A_\sigma < 0.1A$. In this case the following holds:

$$P_{\text{CON}}(x, y) \simeq P_{\text{CON}} = 1 - e^{-\mu_{\text{sink}}},$$ \hspace{1cm} (6)

where $\mu_{\text{sink}} = \rho_0 A_\sigma = IA_\sigma / A$ is the mean number of audible sinks on an infinite plane from any position [20].

$P_{\text{MAC}}(n)$, $n \geq 1$, is the probability of successful transmission when $n - 1$ interfering sensors are present. It accounts for MAC issues and is treated in Section IV for the particular case of the IEEE802.15.4 standard, even though the model is applicable to any CSMA-like protocol. For now we only emphasize that it is a monotonic decreasing function of the number, $n$, of sensors which attempt to connect to the same serving sink. This number is in general a random variable in the range $[0, k]$. In fact, note that in (4) there is no explicit dependence on $k$, except for the fact that $n \leq k$ must hold. Moreover in our case we assume $1 \leq n \leq k$, as there is at least one sensor competing for access with probability $P_{\text{CON}}$ (6).

In [21], Orriss et al. showed that the number of sensors uniformly distributed on an infinite plane that hear one particular sink as the one with the strongest signal power (i.e., the number of sensors competing for access to such sink) is Poisson distributed with mean

$$\bar{n} = \mu_s \frac{1 - e^{-\mu_{\text{sink}}}}{\mu_{\text{sink}}},$$ \hspace{1cm} (7)

with $\mu_s = \rho_s A_\sigma$ being the mean number of sensors that are audible by a given sink. Such a result is relevant toward our goal even though it was derived on the infinite plane. In fact, when border effects are negligible (i.e., $A_\sigma < 0.1A$) and $k$ is large, $n$ can still be considered Poisson distributed. The only two things that change are:

- $n$ is upper bounded by $k$ (i.e., the pdf is truncated)
the density $\rho_s$ is to be computed as the ratio $k/A$ \text{[m}^{-2}\text{]}, thus yielding $\mu_s = k A_s / A$.

Therefore, we assume $n \sim \text{Poisson}(\bar{n})$, with

$$\bar{n} = \bar{n}(k) = \frac{k A_s 1 - e^{-\mu_{sink}}}{A \mu_{sink}} = k \frac{1 - e^{-IA_s}}{I}.$$  \hspace{1cm} (8)

Finally, by making the average in (5) explicit and neglecting border effects (see (6)), we get

$$P_{|k|} = \left(1 - e^{-IA_s}\right) \frac{1}{M} \sum_{n=1}^{k} P_{MAC}(n) \frac{\bar{n}^n e^{-\bar{n}}}{n!},$$  \hspace{1cm} (9)

where

$$M = \sum_{n=1}^{k} \frac{\bar{n}^n e^{-\bar{n}}}{n!}.$$  \hspace{1cm} (10)

is a normalizing factor.

B. Area Throughput

According to the aggregation strategy described in the previous Section, the amount of data samples generated by the network as response to a given query is equal to the number of sensors, $k$, that are present and active when the query is received. As a consequence, the average number of data samples-per-query generated by the network is the mean number of sensors, $k$, in the queried area.

Now denote by $G$ the average number of data samples generated per unit of time, given by

$$G = \bar{k} \cdot f_q = \rho_s \cdot A \cdot \frac{1}{qT} \text{[samples/sec].}$$  \hspace{1cm} (11)

From (11) we have $\bar{k} = GqT$.

The average amount of data received by the infrastructure per unit of time (Area Throughput), $S$, is given by:

$$S = \sum_{k=0}^{+\infty} S(k) \cdot g_k \text{ [samples/sec]},$$  \hspace{1cm} (12)

where $S(k) = \frac{k}{P_{|k|}} P_{|k|} g_k$ as in (1) and $P_{|k|}$ as in (9).

Finally, by means of (9), (10) and (11), equation (12) may be rewritten as

$$S = \frac{1}{qT} \sum_{k=1}^{+\infty} \frac{P_{MAC}(n) \bar{n}^n e^{-\bar{n}}}{k^n n!} \cdot \left(GqT\right)^k e^{-GqT} \cdot \left(k!\right).$$  \hspace{1cm} (13)

IV. THE IEEE802.15.4 MAC PROTOCOL

In [19] an analytical model of the IEEE802.15.4 MAC protocol was presented, considering the non-beacon enabled mode (see the Standard [6]). For details on the protocol we refer to the Standard as well. Here, we just want to underline that a maximum number of times a node can try to access the channel and perform the backoff algorithm, $NB_{max}$, is imposed. According to this, there will be a maximum delay that could affect a packet transmission. We assume that a unit of data (one sample) has a size of 10 Bytes; therefore each node will transmit a packet of size $D \cdot 10$ Bytes. In this case, the maximum delay is equal to $(120 + D) \cdot T$ [19], where $T$ is the time interval needed to transmit 10 Bytes, that is 320 $\mu$s, since a bit rate of 250 $kbit/sec$ is used. We assume that the interval of time between two consecutive queries equals this maximum delay: $T_q = (120 + D) \cdot T$.

To evaluate $P_{MAC}(n)$, the scenario considered consists of $n$ sensors transmitting to a sink with no connectivity problems. A finite state transition diagram is used to model sensor nodes states. Through the analysis of this diagram the probability that a given sensor successfully transmits its packet, $P_{MAC}(n)$, is evaluated. We do not report here the expression of this probability, owing to its complexity, but we refer to [18] and [19], where details on formulae are given and where a validation of the model, through comparison with simulations, is provided for $n \leq 50$. This probability $P_{MAC}(n)$ can be used in (13) for the evaluation of $S$.

In this Section we show some results obtained through the IEEE802.15.4 model, related to a single-sink scenario with $n$ sensors and no connectivity problems. These results are interesting because they motivate the choice of the above described aggregation strategy. It is shown indeed, that given $n$, there exists an optimum value of $D$, $D_{opt}$, maximising the throughput, $S$. Therefore, if sensors are aware of the size $n$ of the cluster they belong to, they could select $D = D_{opt}$, obtained through our results, and transmit the aggregated packet every $D_{opt}$ queries.

In Figs 2 and 3 $P_{MAC}$ and $S$ as functions of $n$ for different values of $D$, are shown, respectively. Results are obtained by fixing $BE_{min} = 3$, $BE_{max} = 5$, and $NB_{max} = 4$ [6]. As we can see, $P_{MAC}$ decreases monotonically by increasing $n$, since the number of sensors competing for the channel increases.

Since here we have ensured connectivity, a single sink and a deterministically fixed number, $k = n$, of sensors competing for access, we have $P_{CON} = 1$ and $P_{|k|} = P_{MAC}$. Hence, the Area Throughput is simply $S = \frac{n}{120 + DT} \cdot P_{MAC}(n)$.

As seen in Figure 3, $S$ presents a maximum. In fact, for small $n$, $P_{MAC}$ approaches zero slower then $1/n$ and thus by increasing $n$, $S$ also increases. On the contrary, for large $n$, $P_{MAC}$ approaches zero faster then $1/n$ and thus by increasing $n$, the product $n \cdot P_{MAC}(n)$ decreases, and so does $S$. The physical interpretation is that too many packet losses occur when traffic is too heavy. The maximum values of $S$ depend on $D$ and are obtained for different values of $n$. As we can see, for $1 < n < 12$, $D_{opt} = 7$; for $12 < n < 18$, $D_{opt} = 5$; for $18 < n < 68$, $D_{opt} = 2$ and for $n > 68$ $D_{opt} = 1$. Therefore, it clearly appears that $D_{opt}$ decreases when increasing $n$.

The aggregation strategy proposed here, is achievable only in case sensors know $n$. This parameter could be estimated by sensors, for example, by computing the number of times the channel is found busy in a given interval of time. The probability to find the channel busy, in fact, is strictly related to $n$. The study of distributed protocols that provide sensors with the knowledge of $n$, is left for future works.
V. Numerical Results

In this Section the behavior of the Area Throughput as a function of $G$ (see (13)) for different connectivity levels and for different values of $D$, is shown.

Let us consider a square area, having area $A = 10^6$ $m^2$, where an average number of 10 sinks are distributed according to a PPP ($I = 10$). We also set $k_0 = 40$, $k_1 = 13.03$, $L_{th} = 120$ and $\sigma = 4$. We first study the case of the IEEE802.15.4 MAC protocol; therefore $T = 320 \mu s e c$ and $q = 120 + D$. Since a typical IEEE802.15.4 air interface is considered, a limit on the number of sensors that could be connected to a given sink should be imposed [22], [23]. To this end, we denote as $n_{max}$ the maximum number of sensors that could be served by a sink and define a new probability (to replace $P_{MAC}(n)$ in (13)) $P'_{MAC}(n)$ given by:

$$P'_{MAC}(n) = \begin{cases} P_{MAC}(n), & n \leq n_{max} \\ P_{MAC}(n_{max}) \cdot \frac{n}{n_{max}}, & n > n_{max} \end{cases}$$

where $P_{MAC}(n)$ is obtained through the model described in Section IV (Figure 2), and $1 - n_{max}/n$ is the probability that a sensor is not served by the sink it is connected to, owing to the capacity constraint. Performance curves are obtained by setting $n_{max} = 20$. Moreover, the case of negligible border effects is considered.

In Figures 4 and 5, $S$ as a function of $G$ for different values of $D$ when $P_{CON} = 1$ and 0.67 respectively, is shown. As it can be observed, in both Figures there exists a value $D_{opt}$ which decreases by increasing $G$. Moreover, from Figure 4 we can see that for $0 < G < 3000$ samples/s (when $I = 10$, $G = 3000$ corresponds to $n = 12$) $D_{opt} = 7$; for $3000 < G < 4500$ samples/s ($G = 4500$ corresponds to $n = 18$) $D_{opt} = 5$; and for $G > 4500$ samples/s $D_{opt} = 2$. Therefore, the behavior of $D_{opt}$ as a function of $G$ is exactly the same of Figure 3.

If we compare Figs 4 and 5, we can observe the effects of connectivity on $S$. As one can see, once we fix $D$, the values of $S$ reached for large offered load are approximatively the same reached when $P_{CON} = 1$. The decrease of $P_{CON}$, in fact, brings to having a lower mean number of sensors per sink, therefore the decreasing of $P_{CON}$ is compensated by an increasing of $P_{MAC}(n)$. However, the behavior of the curves for low values of $G$ is different (the curves have different slopes). If we fix $D = 5$ and we want to obtain $S = 1500$, when $P_{CON} = 0.67$, we need to deploy on average 158 sensors, whereas, when $P_{CON} = 1$, 106 sensors on average are sufficient. Therefore, the loss of connectivity brings to a larger cost in terms of number of sensors that must be deployed to obtain the desired $S$.

To increase the values of $S$, instead, we need to increase $I$. In fact, given a value of $G$, by increasing $I$ the connectivity improves and also the losses due to MAC decrease, since $n$ decreases. We do not show this result here, for the sake of conciseness.

In Figure 6, we adopt a simpler MAC model where the probability of success, $P_{MAC}'(n)$ (to be included in (13)), is a linear function of $n$: $P_{MAC}'(n) = m \cdot n + 1$. In fact, as shown in [5], the probability of success for a non-persistent CSMA protocol may decrease linearly with the number of nodes. We denote by $n^*$ the value such that $P_{MAC}'(n^*) = 0$. In Figure 6 we consider three cases: $m = -0.01$, corresponding to $n^* = 100$; $m = -0.02$, corresponding to $n^* = 50$; and $m = -0.04$, corresponding to $n^* = 25$. As one can see, by decreasing $n^*$ the maximum of $S$ is reached for lower values of $G$. Therefore, for a given value of $G$, by increasing the slope of $P_{MAC}'(n)$, $S$ increases. The maximum value of $S$ obtained with $n^* = 50$ is approximately twice as large as the one obtained with $n^* = 25$, but it is reached for an offered load that is twice over. Therefore, this increase in the maximum value is reached at the cost of deploying more sensors.

VI. Conclusions

A multi-sink WSN where sensor nodes transmit their packets to a sink selected among many, using a CSMA based MAC protocol, is studied. A mathematical framework is developed to evaluate the Area Throughput, that is the amount of samples per second successfully transmitted to the sinks. Sensors are allowed to perform an aggregation procedure, responding sporadically to queries with a single packet composed of all samples taken since the previous transmission. The behavior of the Area Throughput for different packet sizes and connectivity levels, is shown. Results show that there exists a maximum for the throughput and an optimum value of the packet size. This value depends on the mean number of sensors distributed in the network. Finally, the effects of the connectivity on the Area Throughput are evaluated. Results show that when connectivity decreases, the number of sensors that must be deployed to obtain the same Area Throughput increases.

VII. Acknowledgment

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References

Fig. 3. The Area Throughput, $S$, of the IEEE802.15.4 protocol as a function of $n$, for different values of $D$, in a single sink connected case.

Fig. 4. $S$ as a function of $G$, for different values of $D$ when the IEEE802.15.4 MAC protocol is considered and $P_{CO/N}(x, y) = 1$.

Fig. 5. $S$ as a function of $G$, for different values of $D$ when the IEEE802.15.4 MAC protocol is considered and $P_{CO/N}(x, y) = 0.67$.


