Performance Evaluation of UWB Sensor Network with Aloha Multiple Access Scheme

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***Abstract*— The performance of a multi-hop Ultrawideband (UWB) sensor network based on Aloha multiple access technique is evaluated in terms of the average link outage probability and the overall network throughput for different coverage radius of the UWB sensor device. The architecture of the considered sensor network is based on the creation of multi-hop routes using intermediate nodes for each source-destination pair. Packets transmission at each node follows a Poisson distribution with assigned normalized traffic. Performances are obtained using a novel semi-analytical procedure that allows to account for multiple access interference and realistic propagation conditions. The proposed calculation procedure can be used for sensor network design based on Aloha with multi-hop as well as for analysis of an existing installation.**

I. Introduction

Wireless sensor networks are very special networks with large number of nodes collaborating to accomplish common tasks such as environment monitoring and alarm, positioning, location tracking and so on. Sensors are battery powered and their coverage is usually limited to few meters. Thus, in order to cover larger distances, sensors can organize themselves to create a multi-hop communication network. Due to the large variety of services that sensor networks can offer, Ultrawideband (UWB) technology [1], [2] seems to be a viable candidate to offer a unique wireless communication platform for services integration thus avoiding the potential explosion of the number of wireless technologies required to support the different services e.g. Bluetooth, ZigBee, IEEE 802.15.4 etc. When compared to other existing technologies, UWB allows to realize networks with very high capacity, it can support different services characterized by a wide range of bit rates, it ensures low system complexity and, finally, due to the very large bandwidth occupied by the UWB signals the implementation of localization features is easier. One of the main problems in UWB introduction is its coexistence with other systems but this problem can be overcome by adopting suitable countermeasures as demonstrated in [3]. In a sensor network, transmissions of sensor nodes maybe uncoordinated so that collisions resulting from two or more nodes sending data at the same time over the same transmission channel can often occur. Suitable medium access control (MAC) schemes have been developed to coordinate sensors transmissions. Differently from traditional cellular networks interference reduction by scheduling node transmissions is hard to apply in sensor networks [4], [5] where nodes are often deployed in ad-hoc fashion and energy saving is a primary constraint. The performance study of MAC protocols for UWB sensor networks is an active area of research. Several activities in this field are currently performed within the IST-PULSERS project and some of them focus on contention based MAC protocols such as Aloha [6] and carrier sense multiple access (CSMA). However, the application of these protocols to sensor network is not straightforward since both Aloha and CSMA have to be modified to support multi-hop transmissions. As observed in [7] even if CSMA protocols are attractive in single-hop communication scenario, they can significantly limit the performance in a multi-hop scenario where the communication is performed for example by a sequence of minimum-length hops. For this reason in this paper we analyze the performance of UWB sensor networks based on the Aloha protocol for multi-hop networks proposed in [7] in terms of the network throughput as a function of the number of active multi-hop routes in the area and the normalized traffic per node. Single link performance are expressed in terms of the outage probability which accounts for thermal noise and multiple access interference due to other active users that can be arbitrarily sparse in the sensor network area. The calculation procedure presented in this paper is general and allows to account for arbitrary sensor network topologies and realistic propagation including shadowing. It is further shown that the validity of Gaussian approximation [7] for the multiple access interference may lead to a significant under-estimation of the outage probability and then to an over-estimation of performance parameters. The proposed approach can be represented as a two steps procedure. The link outage probability, indicated with P_{out} is first evaluated in a closed mathematical form. Then the unknown probability density functions (pdf) of the random variables appearing in the outage formulation are evaluated using simple and fast Monte Carlo simulations and then used in the calculation of P_{out}. Results on the outage probability are then used to evaluate the traffic throughput for routes with a different number of hops as a function of the number of active links in the area and the normalized traffic per user. The paper is organized as follows. In Section II the main features of the Aloha multi-hop MAC protocol presented in [7] are reviewed. In the same Section

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the aggregate network throughput is defined. In Section III we provide a closed form for the link-outage probability assuming that UWB devices are not power controlled. In Section IV the semi-analytical approach used to evaluate the P_{out} is illustrated. The main characteristics of the UWB-based sensor device are illustrated in Section V. To prove the effectiveness of the proposed procedure results are provided in Section VI. Finally in Section VII conclusions are given.

II. Aloha multi-hop protocol

The main characteristics of the Aloha multi-hop scheme presented in [7] are reviewed in this Section. The technique presented in [7] is an hybrid between circuit and packet switching. A multi-hop route between the source and the destination nodes is initially created by means of a route discovery mechanism such as broadcast percolation in [8]. The nodes in the route are reserved for this communication. When the nodes are mobile the route can be maintained by efficient protocols techniques such as those presented in [9]. After the route creation the source sends the packets to the destination. Transmission in the tube is not continuous but it is packetized. It is further assumed that overall network traffic is Poisson with normalized value $G = \lambda\tau$ where λ is the frequency of packets emission and τ is the packet duration.

A. Network Throughput

The overall network throughput when M routes with identical number of hops, k, are active is:

$$T^{(k)}(M,G) = GP_c^k(M,G), \tag{1}$$

where $P_c(M,G)$ is the average probability of correct reception on a single link i.e. $\overline{P}_c = 1 - \overline{P}_{out}$ where $\overline{P}_{out}$ is the average link-outage probability. The average of P_c is calculated over the area. As shown in the following Section, the P_c depends on M and on the normalized channel traffic, G. We assume that the traffic for each node is G/M where M is the number of active nodes i.e active links in the area. The outage probability P_{out} and then P_c accounts for the network geometry, propagation and multiple access interference. A closed form expression for P_{out} is obtained in the next Section.
Assuming that nodes in the area are always connected using multi-hop routes with minimum number of hops we can define the average aggregate network throughput when M routes are active as:

$$\overline{T}^{(k)}(M,G) = \sum_{k=1}^{\infty} T^{(k)}(M,G)\pi_k = \\ = \sum_{k=1}^{\infty} GP_c^k(M,G)\pi_k \tag{2}$$

where $\{\pi_k\}$ are the probability of having one route with k hops between the source and the destination. The $\{\pi_k\}$ can be determined from coverage analysis and, as shown in Section VI, they depend on the network area dimensions as compared to the coverage area of the single sensor. Definition in (2) is consistent since when $\pi_1 = 1$ and $\pi_k = 0$ for $k > 1$, the common definition of the throughput for single-hop transmissions, is obtained.

III. Calculation of the average outage probability

Indicating with (x_R, y_R) the generic position of a receiver the link outage probability conditioned to (x_R, y_R) is defined as:

$$P_{out} = \mathrm{P}rob\left\{\frac{C}{I+\eta} < \rho_0 | x_R, y_R,\right\} \tag{3}$$

where C is the received power associated to the terminal served by the reference receiver, η is the noise power and I is the intra system interference. Finally $\rho_0 = E_b/N_0 R_b/W_{UWB}$ is carrier-to-interference ratio, R_b is the bit rate and W_{UWB} is the UWB bandwidth. Unless otherwise stated for notational simplicity in the following we omit the indication of the dependence by x_R, y_R in the formulation.
Assuming that the sensor network is composed of M devices that can interfere with the selected receiver, the interference I can be written as:

$$I = \sum_{m=1}^{M} \chi_m L_m P_T, \tag{4}$$

where $\chi_m \in \{0,1\}$, $m = 1,2,...,M$ are binary random variables accounting for the terminals activity whose statistics depend on the selected traffic model; P_T indicates the fixed power level transmitted by the non power controlled UWB terminal. The L_m, $m = 1,2,...,M$ are M statistically independent random variables accounting for the attenuation due to propagation, including shadowing, between the m-th interferer and the reference receiver. Indicating with L the attenuation between the UWB terminal served by the reference receiver, the received power C can be expressed as $C = P_T L$.
From (3) and (4) the link outage probability can be written as:

$$P_{out} = \mathrm{P}rob\{z < 0\} = \int_{-\infty}^{0} f_z(x)dx, \tag{5}$$

where z is

$$z = L - \tilde{I} - \frac{\rho_0\eta}{P_T}, \tag{6}$$

and $\tilde{I} = \rho_0 \sum_{m=1}^{M} \chi_m L_m$ is the normalized interference. Due to the statistical independence of the r.v.s in z, the pdf of z, $f_z(x)$ is:

$$f_z(x) = f_L(x) \otimes f_{\tilde{I}}(-x) \otimes \delta\left(x + \frac{\rho\eta}{P_T}\right). \tag{7}$$

In order to obtain an expression for $f_{\tilde{I}}(x)$ it should be observed that the interference $\tilde{I}$ due to m, $m = 0,1,...,M$ active users in the area can assume the following values:

$$\tilde{I}_0 = 0, \quad \tilde{I}_m = \rho_0 \sum_{n=1}^{m} L_n, \quad m = 1,2,..,M. \tag{8}$$

Indicating with $p_m^{(M)}$ the probability of the event $\{\tilde{I} = \tilde{I}_m\}$, the pdf of z can be written as:

$$f_z(x) = \sum_{m=0}^{M} p_m^{(M)} \left(f_L\left(x + \frac{\rho_0\eta}{P_T}\right) \otimes f_{\tilde{I}}(-x|m)\right), \tag{9}$$

where $\otimes$ denotes convolution and $f_{\tilde{I}}(x|m)$ is the p.d.f. of the random variable $\tilde{I}_m$ in (8), $m = 1,...,M$, representing the interference due to m active users in the area. The $f_{\tilde{I}}(x|m)$ can be further expanded as:

$$f_{\tilde{I}}(x|m) = f_{\rho_0 L_1}(x) \otimes f_{\rho_0 L_2}(x) \otimes \cdots \otimes f_{\rho_0 L_m}(x), \quad (10)$$

and since interfering users are indistinguishable and share the same propagation environment, $f_{\rho_0 L_i}(x) = f_{\rho_0 L_1}(x)$ for each $i = 1, 2, ..., M$. We further assume $f_{\tilde{I}}(x|0) = \delta(x)$.
Substituting (9) in (5) the outage probability can be compactly re-written as:

$$P_{out} = \sum_{m=0}^{M} p_m^{(M)} \beta_m \quad (11)$$

where $p_m^{(M)}$ depends on the selected traffic model and

$$\beta_m = \int_{-\infty}^{0} f_L\left(x + \frac{\rho_0 \eta}{P_T}\right) \otimes f_g(-x|m) dx, \quad m = 0, 1, ..., M. \quad (12)$$

From (12) the β_m are always lower or equal than unity and monotonically increase with m and approach to unity for very large m. Even though not explicitly indicated they depend on the position of the reference receiver i.e. (x_R, y_R) and account for the reduction in the system outage probability due to the network geometry as well as on the path loss characteristics of the propagation environment. The average probability of correct reception $\overline{P}_c$ to be used in (2) can be evaluated after averaging (11) with respect to the spatial coordinates of the receiver thus obtaining:

$$\overline{P}_c = \sum_{m=0}^{M} p_m^{(M)} (1 - B(m)), \quad (13)$$

where $B(m) = E\{\beta_m\}$, $m = 0, 1, ..., M$.
Assuming that UWB devices operate independently and each one is active with probability $\mathrm{P}rob\{\chi = 1\} = p$ and idle with probability $\mathrm{P}rob\{\chi = 0\} = q = 1 - p$, the probability of the event $\{I = I_m\}$ is:

$$p_m^{(M)} = \binom{M}{m} p^m q^{M-m}, \quad m = 0, 1, ..., M. \quad (14)$$

The value of p depends on the selected traffic model. In particular when the time interval between two consecutive packets transmitted by the same UWB device is exponential with frequency λ we obtain:

$$p = 1 - e^{-2G} \quad (15)$$

where $G = \lambda\tau$ is the normalized traffic due to one user transmitting a packet of duration τ [1].

IV. SEMI-ANALYTICAL CALCULATION OF OUTAGE PROBABILITY

To evaluate the system outage probability in (11) and then $\overline{P}_c$ in (13) the pdfs $f_L(x)$, and $f_{\overline{I}_{ext}}(x|m)$ are required. Their approximations can be obtained using the simple and fast Monte Carlo approach based on snapshots generation which is now detailed. Fixing the positions of the receiver in the area and assuming the position of the transmitter inside its coverage area, we first evaluate the attenuation L on the link transmitter-receiver in accordance to the selected propagation model and assuming that the receiver is in the coverage area of the transmitter. The radius of the coverage area is given in Table I. Successively the area is densely gridded and for each point on the grid, the values of the attenuation with respect to the receiver are generated in accordance to the considered propagation model. Generated propagation data are then used to calculate the samples for the r.v.s I_m for each $m = 1, 2, ..., M$. In particular, the statistics of the r.v. I_m representing the interference due to m active users are evaluated considering groups of m randomly selected grid points that are not assigned to the reference receiver. Samples for L and I_m, $m = 1, 2..., M$ obtained from several snapshots are then collected to form the corresponding histograms. Trials are repeated until fluctuations in the histograms frequencies are negligible. Histograms data are then used to obtain a particle approximation for the desired pdfs i.e.:

$$f_L(x) \cong \sum_{p=0}^{K_0} \pi_p \delta(x - l_p), \quad (16)$$

$$f_{\tilde{I}}(x|m) \cong \sum_{j=0}^{K_1} \theta_{jm} \delta(x - g_{jm}), \quad m = 1, 2, ..., M \quad (17)$$

where $\{l_p\}$ and $\{g_{jm}\}$ are the centers of the bins of the histograms for L and I_m. Finally $\{\pi_p\}$ and $\{\theta_{jm}\}$ are the corresponding frequencies obtained after histograms normalization. For simplicity in our calculations we assumed that bins centers were uniformly spaced in dB for every histogram. The accuracy of the particle approximation is determined by the step Δ between two consecutive bins. Accounting for the dimensions of the selected areas, the bins started from -100 dB (or -100 dBm) and spanned a dynamic range greater than 110 dB. From simulation Δ of 0.2 dB was observed to be a good value for our calculations. One of the advantage of using particle approximation is the transformation of the integrals in (12) into sums.

V. UWB DEVICE CHARACTERISTICS

The main parameters of the single UWB-sensor device are summarized in Table I. Both indoor and outdoor propagation environments are considered and they differ for propagation conditions. A single one slope model for path loss has been considered for both environments i.e.:

$$L(d) = L_0 - 10\gamma \log_{10}(d) + \sigma_S x, \quad [dB] \quad (18)$$

where L_0 is the minimum coupling loss evaluated at a reference distance $d_0 = 1$ m assuming free space propagation i.e. $L_0 = -44.5$ dB, γ is the path loss exponent and d is the transmitter-receiver distance. Finally x is a zero mean normal random variable with standard deviation one and $\sigma_S = 2$ dB is the standard deviation of the shadowing. The signal bandwidth W_{UWB} is about 1 GHz and the center operating frequency is $f_0 = 4.0$ GHz. We assume a noise figure $NF = 9$ dB and the

[1]The results in (15) can also be obtained by solving the Kolmogorov time continuous equation for the state probabilities of a Markov chains [10] for a pure-birth process with decreasing transitions rates $\lambda_k = (M - k)\lambda$, $k = 0, 1, ..., M - 1$ where λ is the packet emission rate of a single device.

TABLE I

LINK BUDGET FOR UWB WITH 250KB/S

	Value	
Parameters	**Indoor**	**Outdoor**
$R_b[kb/s]$	250	250
max $P_T[dBm]$	-17	-17
$G_T[dBi]$	0	0
$G_R[dBi]$	0	0
$NF[dB]$	9	9
W_{UWB} [GHz]	1	1
$E_b/N_0[dB]$	20	20
$f_0[GHz]$	4.0	4.0
γ	3	2
$R[m]$	9.7	30.0

transmitter and receiver antenna gains of 0 dBi. Using data in Table I and solving the link budget we obtain the coverage radius R indicated in the Table for both indoor and outdoor transmissions.

VI. RESULTS

To prove the effectiveness of the proposed approach, we consider a rectangular network area. Sensors are randomly positioned in the area in accordance to a uniform spatial distribution. We assume that the route discovery mechanism is able to provide the routes with the minimum number of hops.

A. On the Gaussian Approximation of Interference

In order to simplify the calculation of P_{out}, multiple access interference is considered to be Gaussian[7]. However this assumption is only valid in very limiting conditions. In Fig.1 we plot the β_m as a function of the number of interfering nodes m for two different values of the sensor network area: 10×10 m^2 and 40×40 m^2. To evaluate β_m we considered the formulation of $f_{\tilde{I}}(x|m)$ in (10) and the corresponding Gaussian approximation. The mean and the variance of the Gaussian approximation are evaluated using $f_{\rho_0 L_1}(x)$ that was obtained from simulation. To obtain data in Fig.1 we considered a coverage area for the reference receiver with radius 15m. As shown in Fig.1 Gaussian approximation can provide a good approximation for each m only for areas whose dimensions are comparable with the coverage area of the reference receiver. For larger areas and moderate values of m the central limit theorem cannot be applied due to the larger spread of the values of the attenuation and, in this case, Gaussian approximation underestimates the outage probability. As expected the difference reduces as m increases even though the value of m, for which the exact calculation and the approximation give the same result, increases with the area.

B. Connectivity Analysis

In Table II we indicate the probabilities π_k of having a route with a minimum number of k hops between two generic source and destination nodes in the area. Results in Table II represent limiting distributions that have been obtained by simulation assuming a very large number of UWB devices

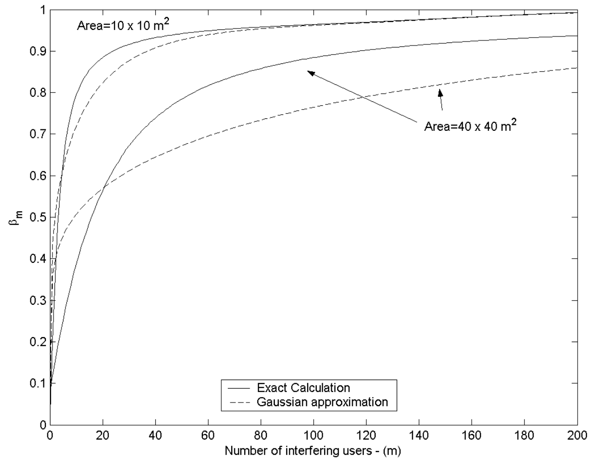

Fig. 1. Values of β_m as a function of the number of interfering users: Exact calculation (continuous lines); Gaussian approximation (dotted lines).

TABLE II

PROBABILITIES π_k OF A ROUTE WITH A MINIMUM NUMBER OF k HOPS - UWB SENSOR COVERAGE RADIUS: 15M

	Area $= 60 \times 30$m	**Area** $= 40 \times 20$m
1	0.0831	0.5001
2	0.1694	0.4130
3	0.2049	0.0867
4	0.1897	0.0002
5	0.1388	0
6	0.0989	0
7	0.0675	0
8	0.0377	0
9	0.0097	0
10	0.0002	0

in the area[2]. Data in Table II are provided for two values for the sensor network area. As expected, the increase in the network area leads to an increase in the maximum number of hops for the routes. In order to outline the dependence of the maximum number of hops on the coverage radius as compared to the network area, in Table III we indicate the maximum and the average number of hops as a function of the sensor coverage radius and assuming a fixed network area. As expected the decrease of the coverage radius leads to an

TABLE III

NUMBER OF HOPS VS RADIUS - AREA: 40×20M^2.

Radius [m]	Max hops	Average hops
5	10	3.98
10	5	2.15
15	4	1.59
20	3	1.31
25	2	1.17
30	2	1.08

increase in the number of required hops. Due to the adoption of Aloha protocol, the evaluation of the average number of hops is important since the average throughput is dependent

[2]The number of UWB-devices was selected in order to have full connectivity i.e. at least one path always exists between two generic nodes.

on the route length (see 2). Given the dimensions of the sensor network area, in order to minimize the number of hops coverage for the single sensor should be enlarged for example by increasing the transmission power P_T even though this solution could be not energy conserving. However, as shown in the following, this may be not a good solution due to the increased interference among the devices and network throughput can decrease.

C. Link Outage probability

In Fig.2 we plot the average P_c as a function of the number of active routes in the area, M. Results have been obtained considering two different area extensions and assuming free space propagation. Results in Fig.2 have been obtained consid-

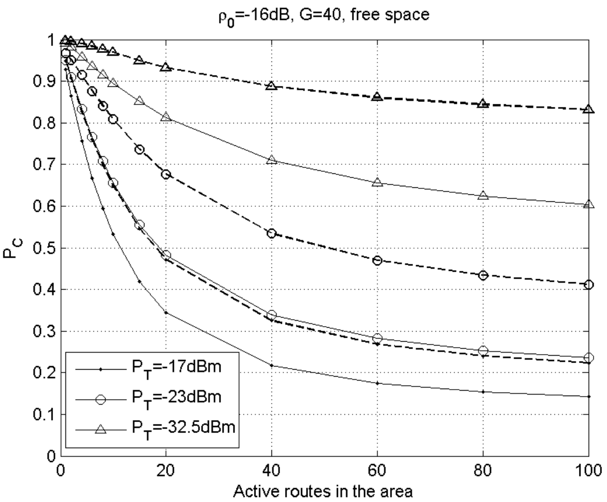

Fig. 2. Average P_c as a function of the number of active routes in the area; different extension of the network area: $80 \times 40\mathrm{m}^2$ (dot.) ,$40 \times 20\mathrm{m}^2$ (cont.).

ering different values of P_T i.e. coverage radius. As expected the P_c decreases with M but, as shown in Fig.2 for fixed M degradation effects due to interference are reduced for larger areas. The reduction of P_c is more evident for large values of P_T i.e. for larger coverage radius since the probability for each relay node of having one or more than one strong interferers in the coverage area increases. As shown in the following this may lead to throughput degradation.

The effects of propagation loss on the P_c are evidenced in Fig.3 where we plot the P_c as a function of active routes in the area for different propagation conditions. As shown in Fig.3 the increased propagation loss can be helpful to reduce interference among devices also for relatively large traffic conditions. However, the reduction of the coverage radius increases the average number of hops in the route and, in principle, this could lead to variation in the aggregate network throughput. Finally in Fig.4 we plot the P_c as a function of the coverage radius of the UWB device and for different values of the network traffic G. Data in Fig.4 have been obtained for small number of active links (e.g. $M = 10$) and for $M = 50$. From the results in Fig.4 the sensitivity of P_c with G is evidenced. As expected, for small G the variations of P_c with the coverage radius are negligible i.e. the activity of the users is

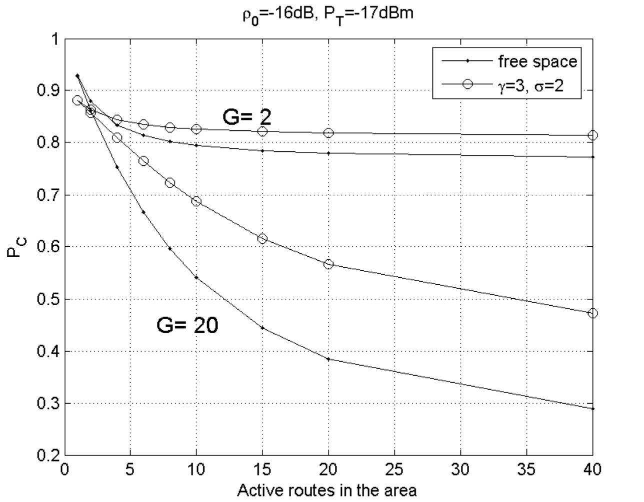

Fig. 3. Average P_c as a function of the number of active routes in the area; different propagation conditions.

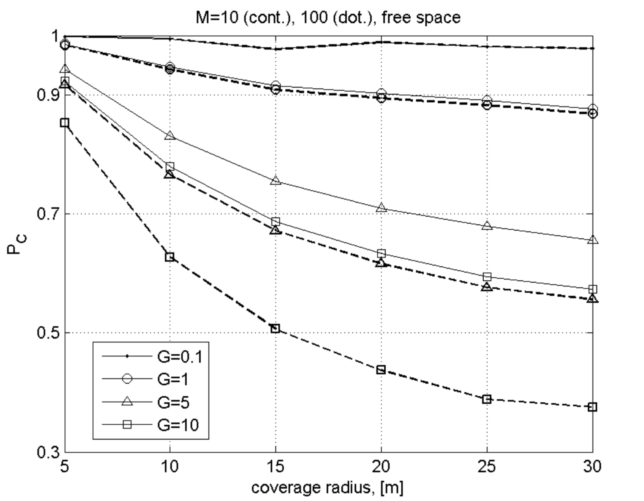

Fig. 4. Average P_c as a function of the coverage radius of the UWB device.

low so that multiple access interference is kept to an acceptable level even for relatively large number of active links. However, when G increases performance becomes dependent on the coverage radius. In particular, it can be observed that when the radius is kept small with respect to the network area[3] for moderate values of M performance are practically independent of M and G and variations in P_c are negligible. However when G and the coverage radius increase, the probability of finding one or more relay nodes in the coverage area of the reference receiver increases and interference becomes higher so that P_c is reduced.

D. Results on the network throughput

In Fig.5 we plot the aggregate network throughput in (2) as a function of the network normalized traffic G for different number of active links M in the area. The π_k in $\overline{T}(M, G)$

[3]this maybe achieved by reducing the transmitter power of the UWB sensors

in (2) have been recalculated to account for different values of the coverage radius. As expected the aggregate throughput

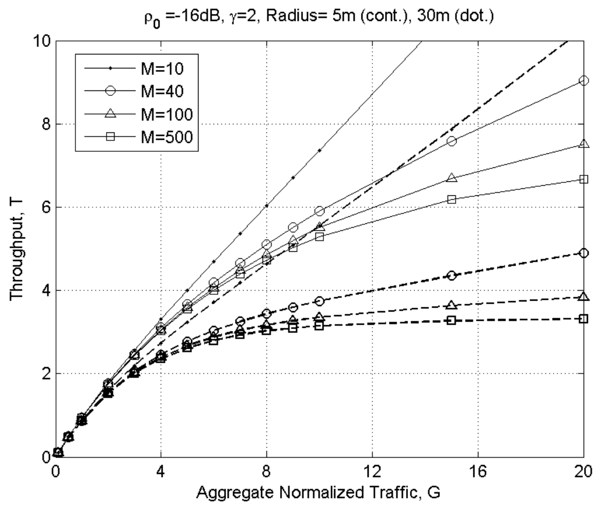

Fig. 5. Average aggregate network throughput as a function of the number of active links.

decreases with M due to the increased interference. From the curves in Fig.5 sensor coverage areas with small radius seems to be preferable since interference among the relay nodes is reduced (on average) with respect to the case of coverage with large radius. In this case, the increased value of P_c in the small coverage case, counterbalances the increase in the average number of hops that, looking (2) in principle, could lead to a reduction in the throughput due to higher values of π_k for $k \geq 2$. Curves like those in Fig.5 give the indication on the maximum normalized traffic that can be sustained by the network without loss. For an area of $40 \times 20\text{m}^2$ this value is about $G = 2$.

VII. Conclusions

We proposed a semi-analytical procedure to analyze the performance of an Aloha-based UWB sensor network. The sensor network performance were evaluated in terms of the aggregate network throughput. The proposed procedure is general and allows to account for arbitrary network topologies and realistic propagation. No approximation are introduced on the statistics of the multiple access interference and the validity of the Gaussian approximation was discussed. The variations of the aggregate network throughput with the coverage area of the UWB sensor were analyzed. It was observed that small coverage radius should be preferable in order to reduce interference effects even though the average number of hops per-route increase.

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