Configurations effects over Swarm Underwater Acoustic Network Performance

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***Abstract*— An underwater swarm network for monitoring and exploration applications is proposed. Specifically, the behavior for different application scenarios with the corresponding performance analysis is presented. The design of an underwater swarm is discussed considering that the main requirement is maintaining the nodes power consumption as low as possible, without any increase of latency in the network. Results show that both average power and latency can be preserved by considering a reasonable number of hops needed to forward information from source to destination. It is verified that the results are influenced by the nodes motion related to the swarm configuration. This study aims to provide some guidelines to develop an autonomous underwater vehicles swarm for underwater applications.**

Keywords – swarm; underwater communications.

I. INTRODUCTION

Over the past few years, a growing interest has been showed for the Underwater Acoustic Networks (UANs) [1] [2]. Several studies have been performed to overcome limitations due to underwater environment, being the UANs affected by different factors influencing performance requirements with respect to the terrestrial ones. Mainly, the temporal and spatial variability, in combination with poor bandwidth availability of the underwater acoustic channel lead to consider the communication range limited and dramatically dependent on both range and frequency [3]. First underwater experimental systems were performed to demonstrate the hardware capabilities and the possibility of underwater communication architecture [4][5].

Our study is directed to a particular UAN, the Swarm Underwater Acoustic Network (SUAN), that is a network, in which the communication paradigm is not a trivial challenge, because the traditional peer-to-peer communication among Autonomous Underwater Vehicle (AUV) devices, as described in [6], is not applicable. Moreover, the particular scenario that is investigated, such as surveillance scenarios with self-organizing capabilities of the network, leads to consider both control and data traffic within the swarm.

Some studies have been performed for this scope, where Ad-Hoc networks [7], or cellular-type [8] networks have been considered to define the underwater network communication. Other studies consider the underwater network as a sensor network. In [9], for instance Fazel et al. consider the performance of a sensor network in terms of energy efficiency, even if their conclusions are not applicable to our case because they assumed a network composed of a large number of fixed nodes anchored to the bottom of the ocean for long period monitoring. The swarm configuration is instead characterized by an aggregate motion due to different modes operability, in which they are involved.

The outcome of this study is the basis for swarm nodes design, in order to define an underwater network for both monitoring and alarm detection applications. A preliminary study has been performed in [10], where the challenges needed at the protocol stack of the AUVs members of the swarm were analyzed. In this work a deeper investigation on swarm nodes motion has been carried out, and how this could impact over network performance has been further investigated in terms of number of hops involved during the forwarding information activities. It is mandatory to maintain this parameter as low as possible to obtain twofold enhancements

- to preserve the *lifetime* of the network: few nodes are involved in the forwarding and consequently their corresponding battery levels are conserved;
- to reduce *latency* in the network: few hops are needed and then less time is spent for sending packets in the very slow underwater channel.

The paper is organized as follows: a brief introduction of the considered application scenarios is provided in Section II, the system model is described in Section III, the test cases are described in Section IV, and the main results are showed in Section V. Finally, in Section VI, the main conclusions are drawn.

II. UNDERWATER SWARM DEFINITION

An underwater swarm network is characterized by nodes very close one to each other, with mobility capability. The structure of the network is that of a distributed network, in which the nodes, through the exchange of control information, will take decisions in collaborative manner.

This system will be able to work in two different modes, which correspond to two different application scenarios:

- Environment Monitoring (**Broadcast Scenario**), in which the nodes perform measurements of proper parameters, measurements of shallow water in the port area and short range communications are considered. From a communication point of view, it

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means that each node is able to communicate with its closest neighbor and to forward information towards a collecting node, which usually is a bottom node with could have also a radio equipment to communicate with a platform at the surface.

- Alarm detection (**Pipeline Scenario**): the swarm detects an alarm occurrence, for instance a measured value of a specific parameter (e.g., oil in the water) is higher than a given threshold in a specific region, and thus, it will be ready to coordinate itself and move towards the area, in which the anomalies have been detected. From a communication point of view, it means that each node is connected only to one next node and all the nodes are allocated in a linear manner. In this case a heavy data transmission is assumed in a directional way.

We remind that, a swarm is characterized by a more complex communication protocol than a peer-to-peer paradigm often applied to AUV devices, and thus the performance of the network will be strictly related to the solutions taken into account at each design level.

III. SYSTEM MODEL

We consider an underwater network of 10 swarm nodes located initially in random positions within a volume of 1000 m×1000 m×150 m. Each node has mobility capability. All the nodes within a coverage range r_{cov} from a given node are considered as its own neighbors. Generally, a network design is based on a suitable trade-off between the coverage radius of each component, and the available transmission power. In addition, to take into account real time data transmission (e.g., submarine video), also the latency constraints need to be considered. Furthermore, the particular mobility availabilities of the swarm nodes need to be analyzed. They have to move, in some situations, very close each to the other, and so interference has to be maintained as low as possible. From these considerations, we have found that all the possible solutions impact, at different levels, over the network performance.

A. Mobility

An important aspect to be considered is the nodes mobility, which determines the different applicative scenarios under test. A 3D model is considered: it is assumed that the position information are stored in all the nodes, and thus a perfect knowledge of exact neighbors' positions is available at any time. The two proposed scenarios imply different algorithms to model nodes motion.

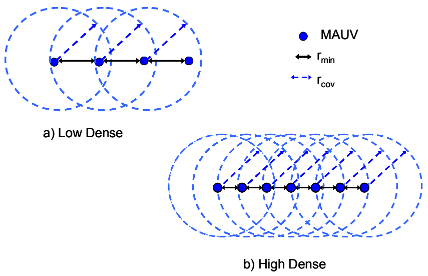

Figure 1. Pipeline scenarios: low (a) and high dense (b) configurations.

Pipeline Scenario - In this scenario the nodes move along the linear conjunction source to destination node. They may assume a dense or a sparse configuration, as depicted in Fig. 1.

Broadcast Scenario – In this case, a control algorithm is implemented able to elaborate an ellipsoid dimension, in which each node has to move inside. The ellipsoid dimensions are dependent on two parameters: the number of nodes, N and the maximum "dimension" of the swarm (e.g., the more distance nodes possible within the swarm), D.

Afterwards, one of the nodes will be elected as the "center" of the ellipsoid (this choice could depend on the target of the swarm, as well as the final configuration selection, i.e., ellipsoid or sphere) and then, others nodes, located outside the ellipsoid, will have to move inside it.

Each of those nodes will move towards the direction of the center of the ellipsoid as far as a distance r_{min} from the node to the surface of the ellipsoid has been reached. r_{min} represents the minimum physical distance, at which the AUV devices have to stay to avoid to crash one to each other. Even in this case, the nodes could stay very close one to each other (high dense configuration) or not (low dense configuration).

A possible sequence of the algorithm states is depicted in Fig. 2. Note that, when the nodes have reached the ellipsoid (Fig. 2b), they form three sub-clusters around the two focuses and the center of the ellipsoid, respectively (each node will choose the closest of these points). To save power, a node stops when has reached a connection to one of the possible sub-clusters (Fig. 2c). After that, sub-clusters will join together by moving their extreme nodes towards the other sub-clusters. During this operation, if a node loses connection from its sub-cluster of origin, another node of its group will "follow" it. Iterating this operation will force the swarm to occupy the maximum possible area of the ellipsoid (Fig. 2d), without the use of a central control.

B. Physical Layer

For the Physical Layer technology, a system based on underwater acoustic signals propagation is considered.

Compared to traditional AUNs, in SUAN the communication range is very short and can be vary from 3 to 100 meters.

In [10], to obtain a good trade-off between bandwidth and efficiency, an isotropic transducer operating at 300 kHz was considered. This value is higher than those used in traditional UAN, but at the same time implies a less harmful multipath effect. The modulation format adopted for acoustic shallow water channel is a Multi-Frequency Shift Keying (M-FSK) with M=4, 8 and 16. This modulation format is more prone to contrast the multipath effects and can allow a low cost modem implementation. Generally, the Signal-to-Noise Ratio (SNR) per bit can be evaluated as [7]

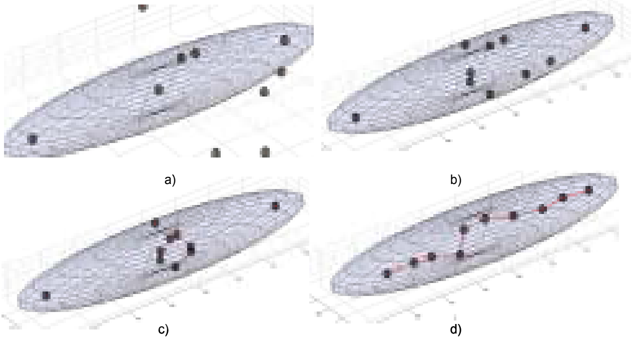

Figure 2. Mobility algorithm: a sequence of a possible configuration: (a) initial nodes' random positions; (b) the nodes enter in the ellipsoid; (c) the formation of the three sub-clusters; (d) final configuration.

$$SNR(d,f) = \frac{P_{TX}(d)}{A(d,f)\cdot N_{Tot}(f)} \tag{1}$$

where P_{TX} is the transmitted power, $A(d,f)$ the attenuation over the link between the transmitting node T_x and the receiving node R_x. $N_{Tot}(f)$ is the overall ambient noise due to turbulence, shipping, waves and thermal noise.

The attenuation is given by [7]

$$A(d,f) = d^k \cdot a^d \tag{2}$$

where k is the energy spreading factor (k is 1 for cylindrical, and 2 for spherical spreading) and

$$a = 10^{\frac{\alpha(f)}{10}} \tag{3}$$

is a frequency-dependent term depending on the absorption coefficient $\alpha(f)$. The absorption coefficient for the frequency range of interest is calculated according to Thorp's expression [11], expressed in dB/km and f in kHz.

A packet is correctly received if the *SNR* (1) exceeds a proper threshold, which can be evaluated by considering the sensitivity level of the receiver. This value is obtained by the data sheets specifications of the transducers. Specifically, for our simulations, an ITC-1089D transducer has been considered. Its specifications are: Receiving Voltage Sensitivity (RVS) of -218 dB re1V/1μPa and Transmit Voltage Response (TVR) exceeding 148 dB re 1μPa/V@1m.

C. Medium Access Control Layer

Different solutions have been proposed in literature for Medium Access Control (MAC) Layer design [12]. For low data rate, with rare collision events, a very simple solution such as ALOHA scheme or its improved version, can be considered. In particular, we have assumed an ALOHA without interference phenomena. Future studies will be necessary to evaluate the effects of the MAC over the system reliability. Hence, a Collision Probability, P_{coll}, will be included in the proposed model.

D. Network Layer

To design a reasonable swarm, two aspects need to be verified: energy saving and latency reduction. These requirements suggest to consider at network level a multi-hop paradigm to forward data among the swarm in order to obtain a reasonable trade-off between the above mentioned opposite factors. The network performance can be thus expressed by the End-to-End Frame Error Probability (*FEP*) for a multi-hop route, which depends on the number of hops needed to forward information from source to destination.

FEP can be evaluated as in [7], resulting

$$FEP = 1-(1-P_b)^{L\cdot n_h} \tag{4}$$

where P_b is the bit error probability for a single node-to-node link, L the frame size in bits, and n_h is the number of hops needed to forward data within the swarm. Obviously, n_h strictly depends in what configuration the swarm is, and then by its geometrical characteristics. The bit error probability depends on both the modulation format and the propagation channel. An M-FSK modulation format over a Rayleigh fading channel is considered. Therefore, the P_b of an M-ary orthogonal signal can be expressed as [13]

$$P_b = \frac{M/2}{M-1}\cdot\sum_{m=1}^{M-1}\frac{(-1)^{(m+1)}\cdot\begin{pmatrix}M-1\\ m\end{pmatrix}}{1+m+m\gamma} \tag{5}$$

where M is the level of the M-FSK modulation format, and γ the linear expression of the *SNR* resulting from (1).

IV. TEST CASES

Performance analysis has been repeated for both the proposed scenarios. Different considerations have been carried out for each case, strictly related to the different mobility models that swarm can assume. Specifically,

- **Pipeline Scenario -** AUVs place themselves along the linear conjunction between source to destination to forward information in efficient manner.
- **Broadcast Scenario** - The swarm can assume two different geometrical shapes: Sphere or Ellipsoid.

For each case, it is possible consider two configurations:

- *Low dense configuration:* AUVs assume a uniform distribution inside the limited area to maximize the swarm coverage area.

- *High dense configuration:* AUVs are located very close each to other. They are at the minimum distance permitted by their physical dimension.

V. Performance Analysis And Trade-Offs

Performance analysis has been carried out by Matlab [14] and system performance has been evaluated and compared with different test cases described in Section IV. More deeply, we have investigated the performance of the swarm network in terms of *FEP* according to [4]. We have firstly evaluated the *FEP* by considering the number of hops needed to reach destination by theoretical considerations in different test cases, taking into account the main system constraints: the minimum distance, r_{min} , and the coverage radius of each node, r_{cov}. After we have evaluated n_h by considering the outcome by both mobility, and physical simulations.

Specifically:

- the outcome by the mobility model will permit to evaluate the distance of each node in different configurations;
- the outcome by the physical model will permit to evaluate the corresponding *SNR* (at each distance calculated by the mobility schemes) of the transmitted signal for each node. The average SNR value for each test case will be considered for the *FEP* evaluation.

These evaluations have been performed for each M-ary modulation format. We proposed some equations to define a number of hops for each scenario as described in the following subsections.

A. Pipeline Scenario

We have evaluated the number of hops taking into account geometric configurations of the swarm for both high and low dense case. We have reported only theoretical considerations because no difference has been found by simulation results.

- **Low Dense Pipeline** – In this case the nodes are located at the maximum distance allowable for a fully connected swarm, r_{cov} (Fig. 1a), and the number of hops is given by

$$n_{h_{LP}} = N - 1 . \tag{6}$$

- **High Dense Pipeline –** In this case the nodes are located at the minimum distance allowable, r_{min} (Fig. 1b) and thus the number of hops to cover the distance D is obtained as the ratio D to r_{cov}

$$n_{h_{HP}} = \frac{D}{r_{\text{cov}}} = \frac{(N-1)\cdot r_{\min}}{r_{\text{cov}}} = (N-1)\cdot \frac{r_{\min}}{r_{\text{cov}}} . \tag{7}$$

B. Broadcast Scenario

For this scenario we have firstly evaluated n_h with theoretical considerations, after we have repeated the same analysis by considering the outcome of the mobility simulator.

1) **Theoretical Model** – The model is based on geometrical considerations of the different configurations that the swarm assumes. For each test case, the maximum number of hops needed to forward information from source to destination has been evaluated.

a) High Dense Sphere Configuration - The maximum number of nodes can be evaluated according to (8), as the ratio between two sphere volumes: the Physical Sphere, V_{min} and the Coverage Sphere V_{cov}. This assumption is justified by considering that each node is very close to each other, and thus the Coverage Sphere of each node overlaps with the other ones (Fig. 3b),

$$n_{h_{DS}} = \frac{V_{\min}}{V_{\text{cov}}} = \frac{N\frac{4}{3}\pi\cdot r_{\min}^3}{\frac{4}{3}\pi\cdot r_{\text{cov}}^3} = N\cdot\left(\frac{r_{\min}}{r_{\text{cov}}}\right)^3 . \tag{8}$$

b) Low Dense Sphere Configuration – The number of hops can be evaluated according to (9), where D is the diameter of the sphere, in which the swarm can stay and d is the maximum distance between two neighbors nodes, which corresponds, in the worst case, to r_{cov} (Fig. 3a). The diameter D can be calculated as a function of the volume of the sphere that (in the worst case) contains N spheres of r_{cov} /2 radius. In this case, the maximum hops number is

$$n_{h_{LS}} = \frac{D}{d} = \frac{\sqrt[3]{\frac{6}{\pi}V}}{r_{\text{cov}}} = \frac{\sqrt[3]{\frac{6}{\pi}N\frac{4}{3}\pi\left(\frac{r_{\text{cov}}}{2}\right)^3}}{r_{\text{cov}}} = \sqrt[3]{N} . \tag{9}$$

c) High Dense Ellipsoid Configuration – As in the high dense sphere case, the nodes are very close one to each other within a “thin” sphere that converges to an ellipsoid; if the ellipsoid is very thin means that the swarm assumes a quasi-linear configuration and thus the number of hops can be calculated by (7), whereas if the ellipsoid has its geometrical parameters of the same value (i.e., a=b=c), the ellipsoid converges to the sphere case and the number of hops is expressed by (8). For all the other cases, the number of hops is given by

$$N\cdot\left(\frac{r_{\min}}{r_{\text{cov}}}\right)^3 < n_{h_{HE}} < (N-1)\cdot\frac{r_{\min}}{r_{\text{cov}}} . \tag{10}$$

d) Low Dense Ellipsoid Configuration – As in the low sphere configuration, the maximum distance allowable between two nodes is determined by the minimum *SNR* required by r_{cov}. If the ellipsoid is very thin, it collapses to a linear distance such as the pipeline, and the number of hops is equal to *N*-1, while if the ellipsoid collapses to a sphere, the number of hops can be expressed by (9). Even in this case the average configuration with a canonic ellipsoid leads to a number of hop as:

$$\sqrt[3]{N} < n_{h_{LE}} < N-1. \tag{11}$$

2) **Numerical Results** – The results obtained by using theoretical approaches have been confirmed by simulation outcomes. We have simulated the swarm mobility models and after evaluated the number of hops needed for each configuration. In our simulations, we assume 10 AUVs in the swarm, with r_{cov}=80 m and r_{phy} =3 m. The output of the mobility algorithm is the *Hop Matrix*, M_{Hop}, in which the i-th column represents the number of hops needed to the i-th node to reach the j-th node. We have verified that:

a) High Dense Sphere Configuration – Each node is directly connected to all the others, and then the M_{Hop} will be composed of all 1, i.e., only one hop is needed to reach the destination.

b) Low Dense Sphere Configuration – In this case the details of the M_{Hop} are shown in Fig. 4, in which we can note that the maximum number of hops is 6, due to the spherical symmetry of the nodes configuration.

c) High Dense Ellipsoid configuration – Even in this case the M_{Hop} matrix is fulfilled as the High Dense Sphere one.

d) Low Dense Ellipsoid Configuration – The number of hops increases significantly with respect to the previous case, due to the increase of the swarm area.

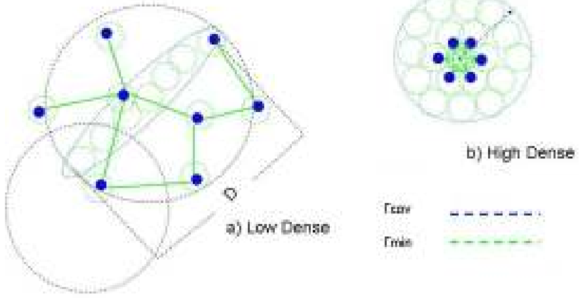

Figure 3. Sphere scenarios: low (a) and high (b) dense configurations.

$$\begin{pmatrix} 1&4&2&1&3&5&1&2&5&3\\ 4&1&5&3&1&1&4&2&1&2\\ 2&5&1&2&4&6&1&3&6&4\\ 1&3&2&1&2&4&1&1&4&2\\ 3&1&4&2&1&2&3&1&2&1\\ 5&1&6&4&2&1&5&3&1&3\\ 1&4&1&1&3&5&1&2&5&3\\ 2&2&3&1&1&3&2&1&3&1\\ 5&1&6&4&2&1&5&3&1&3\\ 3&2&4&2&1&3&3&1&3&1 \end{pmatrix} \quad \begin{pmatrix} 1&4&2&6&2&7&3&1&1&5\\ 4&1&6&2&2&3&1&5&3&1\\ 2&6&1&8&4&9&5&1&3&7\\ 6&2&8&1&4&1&3&7&5&1\\ 2&2&4&4&1&5&1&3&1&3\\ 7&3&9&1&5&1&4&8&6&2\\ 3&1&5&3&1&4&1&4&2&2\\ 1&5&1&7&3&8&4&1&2&6\\ 1&3&3&5&1&6&2&2&1&4\\ 5&1&7&1&3&2&2&6&4&1 \end{pmatrix}$$

Figure 4. Hop Matrix – Low Dense Sphere Configuration (left) and Low Dense Ellipsoid Configuration (right).

In this case, the maximum number of hops reaches the Pipeline Low case, i.e., 9 hops. It means that all the nodes are involved in the forwarding activities (Fig. 4).

Figures 5-8 show the performance in terms of *FEP* for each case under test for both theoretical and numerical results, respectively. The evaluations have been repeated for M-FSK with *M*=4,8, and 16. In the figures only 4-FSK and 16-FSK have been reported because the 8-FSK results appeared not significantly different from the 4-FSK ones.

Specifically, Fig. 5 shows the theoretical *FEP* evaluation for pipeline scenarios. Figures 6-7 show *FEP* evaluations for low dense sphere and ellipsoid, respectively by considering both theoretical and numerical models. Fig. 8 depicts high dense sphere and ellipsoid cases. In the latter case theoretical and numerical results are coincident, and thus only one (theoretical) has been reported. We have verified that 16-FSK requires a lower *SNR* value than 4-FSK to achieve the same *FEP* level. This attitude becomes more evident in the high dense cases. The sphere configurations are characterized by better performance with respect to the other ones, while the ellipsoid scenarios assume middle performance between the sphere and the pipeline cases. All the theoretical considerations are confirmed by numerical results, showing a good confidence level for the proposed mobility algorithm.

VI. CONLCUSIONS AND FUTURE WORK

Underwater swarm networks have been considered to define the requirements to be satisfied in different application scenarios. Performance evaluations by comparing different operability modes for a swarm network have been carried out. By numerical results we have verified that the performance strictly depends on the different swarm configurations. The power consumption and the latency have to be taken into account, which are the main constraints for alert applications. A good trade-off has to be achieved to obtain solutions suitable to real underwater context. Future studies will be to consider a more complex physical layer model, which includes environment information and its variability (i.e., temperature and salinity profiles), remembering that in underwater network design the upper layers of nodes are highly constrained by the physical layer parameters.

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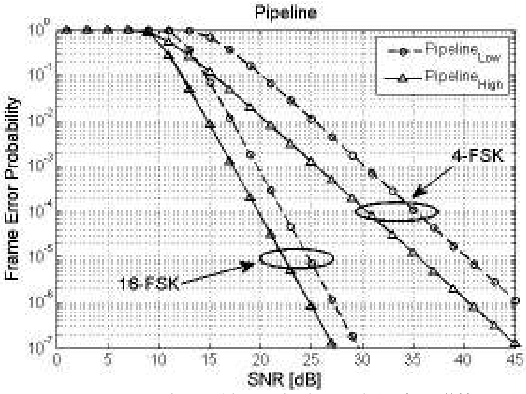

Figure 5. FEP comparison (theoretical results) for different pipeline scenarios.

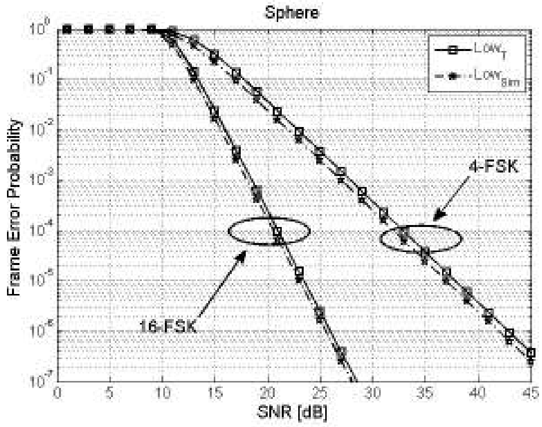

Figure 6. FEP comparison (theoretical and numerical results) for different sphere low dense configurations.

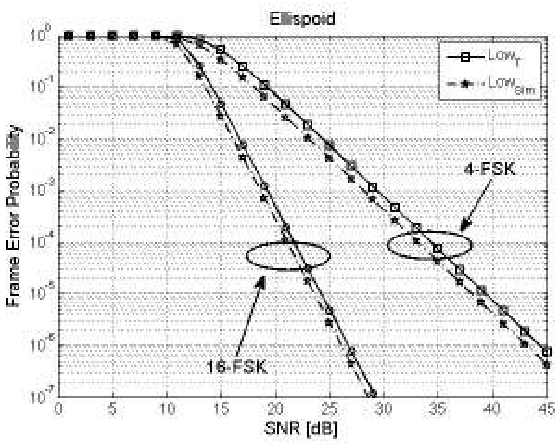

Figure 7. FEP comparison (theoretical and numerical results) for different ellipsoid low dense configurations.

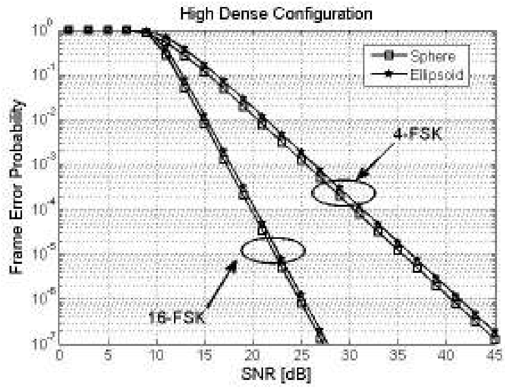

Figure 8. FEP comparison (theoretical results) for different high dense configurations.

REFERENCES

[1] E. M. Sozer, M. Stojanovic, and J. G. Proakis, ”Underwater acoustic networks,” Oceanic Engineering, IEEE Journal of, 2000, vol. 25, pp. 72-83.

[2] J. G. Proakis, E. M. Sozer, J. A. Rice and M. Stojanovic, “Shallow Water Acoustic Networks,” IEEE Communications Magazine, November 2001, pp. 114-119.

[3] I. F. Akyildiz, D. Pompili, and T. Melodia, ”Challenges for Efficient Communication in Underwater Acoustic Sensor Networks,” ACM Sigbed Review, vol. 1, no. 2, July 2004.

[4] J. Rice, ”SeaWeb acoustic communication and navigation networks,” in Proc. Int. Conf. Underwater Acoust. Meas.: Technol. Results, Crete, Grece, Jun. 2005, pp. 2007 - 2017.

[5] M. Grund, L. Freitag, J. Preisig, and K. Ball, ”The PLUSNet underwater communications system: Acoustic telemetry for undensea surveillance,” in Proc. IEEE OCEANS’06 Conf. on, Boston, MA, Sep. 2006.

[6] S. M. Smith, J. C. Park, and A. Neel, ”A peer-to-peer communication protocol for underwater acoustic communication,” in OCEANS’97, Halifax, Nova Scotia, Oct. 1997, pp. 268-272.

[7] A. Stefanov and M. Stojanovic, ”Design and Performance Analysis of Underwater Acoustic Networks,” IEEE Journal on Selected Areas in Communications (JSAC), Special Issue on Advances in Military Communications and Networking, Vol. 29, Issue 10, pp. 2012-2021.

[8] M. Stojanovic, ”Design and Capacity Analysis of Cellular Type Underwater Acoustic Networks,” IEEE Journal of Oceanic Engineering, Vol.33, No.2, Apr. 2008, pp. 171-181.

[9] F. Fazel, M. Fazel, and M. Stojanovic, ”Random Access Compressed Sensing for Energy-Efficient Underwater Sensor Networks,” IEEE Journal on Selected Areas in Communications (JSAC), Special Issue on Energy-Efficient Wireless Communications, Vol.29, n. 8, Sep. 2011.

[10] M. Tabacchiera, S. Persia, C. Lodovisi, and S. Betti, ”Performance Analysis of Underwater Swarm Sensor Networks,” ’Broadband and Wireless Computing, Communication and Applications (BWCCA), 2011 Int. Conf. on, Barcellona, Spain Oct. 2011, pp. 333-338.

[11] L. Berkhovskikh and Y. Lysanov, ”Fundamentals of Ocean Acoustics,” New York, Springer, 1982.

[12] C. Petrioli, R. Petroccia, and M. Stojanovic, ”A Comparative Performance Evaluation of MAC Protocols for Underwater Sensor Networks,” in Proc. IEEE Oceans’08 Conf. on, Quebec City, Canada, Sep. 2008.

[13] J. G. Proakis, “Digital Communications” 2nd Ed., McGraw-Hill, 1989.

[14] http://www.mathworks.com