

IDENTIFYING THE OPTIMAL TRANSMISSION RANGE IN DEPTH-BASED ROUTING FOR UWSN

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ABSTRACT

Routing in Underwater Wireless Sensor Networks (UWSNs) is a challenging problem because of the intrinsic characteristics of this class of wireless networks (long propagation delay, mobility of nodes, etc.) and because of the performance indices that must be taken into account, such as the network throughput, the packet delivery ratio and the energy cost. In particular, routing algorithms must grant a low energy cost in order to maximise the lifetime of the network's nodes.

In this study we focus on a popular routing protocol for UWSNs, namely the Depth-Based Routing (DBR). Specifically, we study the impact of the transmission range of the nodes on the network performance indices, with particular attention to its energy efficiency. The study is based on an extensive set of simulations performed in AquaSim-NG using a library that has been developed with the aim of providing an accurate estimation of the nodes' energy consumption and is integrated with the tools previously developed for the study of UWSNs. The main outcome of our work is showing the relation between transmission range providing the optimal DBR energy efficiency and the density of the nodes in a UWSN.

INTRODUCTION

Routing protocols in UWSNs aim at providing high network connectivity, low energy consumption and low packet delay by capitalizing the intrinsic characteristics of acoustic communication. From the functional point of view, routing protocols in UWSNs have to transmit the sensed data collected by the underwater nodes to some sink nodes on the surface which will eventually transmit them to the base-station to be processed. Underwater nodes are usually equipped with batteries which are difficult to replace or recharge and for this reason energy preservation must be a key-factor in the design of routing algorithms and a simple flooding strategy turns to be highly inefficient. Moreover, the mobility of nodes

makes strategies based on the identification and storing of routes hard to apply in practice. Routes are continuously broken and new ones are created (Pompili and Akyildiz 2009). In the literature, several strategies have been proposed in order to introduce new routing protocols or to optimize previously proposed ones including specific node deployment strategies, localization schemes and transmission range selection.

Depth-Based Routing (DBR) (Yan et al. 2008) is a localization-free routing scheme and only relies on depth information of nodes in order to transfer data from the source to the sink node. When a node transmits a packet all of its neighbors can receive it due to the broadcast nature of the considered acoustic transmission, however only the low-depth neighbors are eligible for forwarding. This allows the algorithm to control the flooding and reduce the probability of interferences. In DBR we assume that each node does not have knowledge of its absolute position in the water but knows its depth thanks to a pressure-based sensor. When a packet is sent, the protocol aims at selecting the neighbor which is nearest to the surface as forwarder so that the number of hops is reduced and, as a consequence, the end-to-end delay and the energy consumption are also reduced. The forwarder selection is based on two strategies: the first is the introduction of the depth threshold which states the depth over which a node cannot be a forwarder, while the second is the holding time, i.e., a delay whose duration is proportional to the depth difference between the sender and the candidate forwarder. Hence, when a node receives a packet that must be forwarded, it waits for the expiration of the holding time and decides to retransmit the packet only if no other node in its receiving range has previously forwarded it.

DBR is considered as the pioneer and one of the most reliable schemes in the category of opportunistic routing algorithms for UWSNs and is still largely studied in the recent literature about UWSNs. A detailed survey on depth based routing and other opportunistic routing protocols can be found in (Coutinho et al. 2016). In particular, the authors classify the opportunistic routing schemes according to their candidate and forwarder selection procedures.

The actual deployment of a UWSN using DBR must face some design problems concerning the identification of the optimal configuration parameters for the protocol

such as the constants for the computation of the holding time and the depth threshold value. However, it should be clear that also the configuration of the physical layer parameters affects the performance of the network. Specifically, the node transmission range strongly influences the energy cost of the protocol. High transmission ranges consume more energy and increase the probability of interferences but allows DBR to cover longer distances with one hop. This consideration suggests that there must exist optimal values for the transmission ranges (see (Zorzi and Pupolin 1995) for an analytical model of terrestrial networks addressing this problem). Another important observation is that the optimal transmission range depends on the node density, since lower densities imply longer transmission radius in order to avoid packet losses due to the absence of eligible neighbours in the sender range.

RELATED WORK

Harris et.al (Harris III and Zorzi 2007) propose a simulation model to compute an accurate transmission power required to meet the SNR threshold of $20dB$ at the receiver for various intermediate distances among the nodes. They also devise a model for an acoustic channel and provide its comprehensive implementation in NS2 by employing passive sonar equation. We use this work for modelling the correct transmission events in our simulation model.

In the literature of underwater networks, aspects of physical layer have been taken into account for improving the performance of routing and MAC protocols. To this aim, efficient localization strategies, optimal transmission range selection and design of operational modes of acoustic modems showed to be helpful in increasing the network lifetime, improving the robustness of its connectivity and decreasing the end-to-end delay.

Porto et.al (Porto and Stojanovic 2007) propose an extended form of Distance-Aware Collision Avoidance Protocol (DACAP) by augmenting it with optimized transmission power and range selection for sensor nodes. The fine control of these parameters leads to an improvement of the energy efficiency while the network connectivity is preserved. Similarly to the outcome we have in this paper, the authors find out that the selection of the optimal transmission range in DACAP depends on the network density. However, in contrast with DACAP, it is not necessary true for DBR that the optimal transmission range is the minimum radius that ensures the network connectivity as it will be evident from our experiments. In (Kim et al. 2007), the authors suggest a novel routing scheme supplied with adjustable transmission range technique for sensor nodes with the aim of minimizing the end-to-end delay and increasing the energy efficiency. The proposed Energy efficient Innovative Time Reduction Communication (E-ITRC) protocol exploits the relay-based communication for reduc-

ing the expected number of intermediate hops towards base station. However, E-ITRC adopt a dynamic transmission range adjustment and hence, with respect to DBR, it requires a much more sophisticated protocol implementation. Gao et.al (Gao et al. 2012) provide an analytical model for the evaluation of the network power consumption. Based on this model, they propose a method for obtaining the optimal transmission range for a randomly deployed network. Finally, they examine the impact of the transmission range on some relevant performance indices such as the energy efficiency and the network connectivity. However, only one hop transmissions have been considered and the abstraction of the analytical model makes it hard to derive a practical rule for setting the protocol parameters.

Although all of these papers aim at specifying the optimal transmission range for the combination of some MAC layers and routing protocol, still to the best of our knowledge there is no work considering DBR optimal transmission ranges by taking into account the detailed implementation of the network (e.g., busy terminal problems and so on). To cover this gap, we adopt our implementation (Jafri 2017) of DBR in AquaSim-NG (Martin et al. 2015) which is a NS3 (Carneiro 2010) based simulator and its libraries have been designed with a more efficient and detailed simulation framework for UWSNs. AquaSim-NG is an enhanced version of AquaSim (Xie et al. 2009) which is a specialized simulator for underwater networks and contains complete layered architecture.

Contributions In this paper we address the problem of estimating the optimal transmission range for DBR based UWSNs by resorting to a detailed simulation model that takes into account a broad set of relevant aspects of actual network deployments. To this aim, we extended the DBR implementation of AquaSim-NG (Martin et al. 2015) in order to include an accurate modelling of nodes' energy consumption taking into account the operational modes of the modems. The simulator is open access and can be downloaded from the official repository of AquaSim-NG (Martin 2016, Jafri 2017). We emphasized the cross-layer interactions between the physical and the routing layer. Finally, our simulation model is able to tackle the problem of the busy terminal which is well-known to be important for the estimation of the network energy efficiency (Yan et al. 2008). We have considered several scenarios and we have experimentally derived a relation between the optimal transmission range and the node density.

DBR AND ITS SIMULATION MODEL

In this section we briefly recall DBR and present the main features of our simulation model. We take a bottom up approach based on the layer partition of the

protocol stack. Particular attention will be devoted to the analysis of the power consumption and the loss probability at the physical layer.

Modelling the power consumption at the physical layer

At the physical layer, the transmission power consumption of an acoustic signal in UWSNs is computed by using the passive sonar equation presented in (Harris III and Zorzi 2007, Domingo and Prior 2008) which gives the Signal to Noise Ratio (SNR) at the receiver based on some parameters among which a major role is played by the transmission power and the Attenuation-Noise (AN) factor. This last factor is computed according to the well-known Thorp's formula (Harris III and Zorzi 2007):

$$10 \log_{10} \alpha(f) = \begin{cases} 0.11f^2/(1+f^2) + 44f^2/(4100+f^2) \\ + 2.75 * 10^{-4}f^2 + 0.003 & \text{if } f \geq 0.4\text{kHz} \\ 0.002 + 0.11(f/(1+f)) + 0.011f & \text{if } f < 0.4\text{kHz} \end{cases}$$

where f is the frequency measures in kHz and $\alpha(f)$ is measured in dB/km .

Total attenuation $A(l, f)$ is computed by combining the total absorption loss $\alpha(f)$ and the spreading loss:

$$10 \log A(l, f) = k * 10 \log(l) + l * 10 \log(\alpha(f)), \quad (1)$$

where k is the spreading coefficient. Following (Harris III and Zorzi 2007), we compute the total attenuation in $dbre\mu Pa$ which is the standard unit used to compute the signal loss in acoustic communications. The first term of Equation (1) models the spreading loss and the second the attenuation loss.

The noise model consists of four main components: the wind factor ($N_w(f)$), the shipping factor ($N_s(f)$), the thermal factor ($N_{th}(f)$) factor and the turbulence ($N_t(f)$) factor which are defined as follows:

$$\begin{aligned} 10 \log(N_t(f)) &= 17 - 30 \log(f), \\ 10 \log(N_s(f)) &= 40 + 20(s - 0.5) + 26 \log(f) \\ &\quad - 60 \log(f + 0.03), \\ 10 \log(N_w(f)) &= 50 + 7.5w^{1/2} + 20 \log(f) \\ &\quad - 40 \log(f + 0.4), \\ 10 \log(N_{th}(f)) &= -15 + 20 \log(f), \end{aligned}$$

where s is the shipping constant and its value varies from 0 to 1. w is the wind constant having a positive value which shows the speed of wind. A discussion about practical values assumed by these constants can be found in (Harris III and Zorzi 2007). Finally, to compute the total noise loss NL we combine these components:

$$NL = N_t(f) + N_s(f) + N_w(f) + N_{th}(f).$$

Notice that transmission frequency (f) dominantly affects the level of noise as higher frequency tends to increase the noise loss of signal. Moreover passive sonar equation also uses Directivity Index (DI) which shows the ability of receiver's hydrophone to avoid unwanted noise. We assume its value as 3 dB (Domingo and Prior 2008).

The transmission power required to achieve a target SNR at receiver over distance d can be computed using the algorithm (1) as follows (Harris III and Zorzi 2007):

Algorithm 1 Computation of transmission power consumption

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1:  $AN[i] \leftarrow$  Attenuation Noise factor for  $i$ th frequency
2:  $of$  signal bandwidth
3:  $k \leftarrow$  Spreading coefficient
4:  $d \leftarrow$  Euclidean distance between nodes
5:  $Thorp(f[i]) \leftarrow$  attenuation loss for  $i$ th frequency
6:  $of$  signal bandwidth
7:  $Noise(f[i]) \leftarrow$  noise loss for  $i$ th frequency of signal
8: bandwidth
9:  $Pr \leftarrow$  SNR threshold of receiver
10:  $Pt \leftarrow$  Transmission power required to successfully
11: transmit signal
12:  $Num\_freq \leftarrow$  Number of frequencies in the
13: bandwidth of signal
14:  $DI \leftarrow$  Directivity Index

15: for  $i \leftarrow 0$  to  $Num\_freq$  do
16:    $AN[i] \leftarrow - (k * 10 * \log_{10}(d) + d * Thorp(f[i]) +$ 
    $DI + \log_{10}(Noise(f[i])))$ ;
17:   if  $AN[i] > AN[max\_index]$  then
18:      $max\_index \leftarrow i$ 
19:   end if
20: end for
21:  $Pt = Pr - AN[max\_index]$ ;
22: return  $Pt$ ;
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Algorithm (1) accurately predicts the required transmission power considering various distances between the communicating nodes. Figure 1 shows the transmission power required to successfully achieve the signal strength of $20 dbre\mu Pa$ at the receiver. By targeting specific SNR at the receiver, the passive sonar equation gives the required transmission power which majorly increases with the distance (see, e.g., (Urick 1983, Brekhovskikh and Lysanov 2003, Harris III and Zorzi 2007)).

DBR network layer and its simulation model

In DBR, nodes use pressure-based sensors to estimate their depth and rely on this information to transmit the packets to the on-surface sink. As DBR is a controlled-flooding based scheme the correct setting of its param-

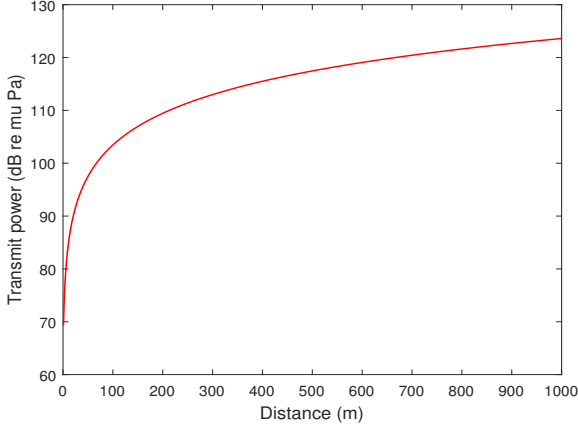


Figure 1: Required transmission power for various distances

eters, namely the *depth threshold* and the *holding time*, plays a pivotal role for obtaining high performance with a low energy consumption. Intuitively, the forwarder selection is based on the packet scheduled sending time which is decided on the basis of computation of the holding time. The packet holding time is proportional to the depth difference between the sender and the candidate forwarder and hence it favors the nodes that allow the packets to cover longer distances towards the sinks. The depth threshold is used to prevent nodes with low depth difference to become candidate forwarders. During the holding time duration, nodes discard the enqueued packet upon finding its transmission from a lower depth neighbor. DBR targets lowest depth neighbor of sender as an optimal packet forwarder which is also helpful in suppressing transmissions of other eligible neighbors of sender node. Thanks to its stateless and distributed nature, DBR is capable of handling the routing in UWSNs with high node mobility and maintains a low resource usage (there is no need to store routing tables) and easiness of implementation. According to (Yan et al. 2008) in DBR the holding time is obtained as follows:

$$f_{\text{DBR}}(d) = \left(\frac{2\tau}{\delta}\right) * (T - d),$$

where T is the maximal transmission range of a node, τ is the maximum propagation delay of one hop, i.e., $\tau = T/v_0$ (where v_0 is the sound propagation speed in the water), d is the depth difference between the sender and the receiver and δ is a scaling factor of the holding times which is chosen in order to achieve the optimal performance of the network and to minimize the hidden terminal problem. The analysis of the impact of these configuration parameters on the network performance has been done in (Yan et al. 2008). Nevertheless, in this paper we focus on the impact of a configuration parameter at the physical layer, namely the transmission

range, on the network performance expressed in terms of the expected packet delivery ratio and the energy cost.

PROBLEM STATEMENT

When we deploy an UWSN using DBR routing protocol, the setting of the network layer parameters, i.e., the holding time and the depth threshold, is helpful to minimize the energy consumption but may be not sufficient. In fact, the selection of an optimum transmission range at the physical layer may drastically reduce the network energy cost (and hence its lifetime) while maintaining a reasonably high packet delivery ratio. Transmission range plays a pivotal role in determining the energy consumption and the packet delivery ratio in a UWSN implementing DBR. Let us focus on the energy cost defined as the expected energy required to successfully send a packet to the sink node. Short transmission ranges cause problems in the network connectivity and hence frequently require packet retransmissions that cause a high energy consumption. On the other hand very long transmission ranges require more energy per packet and cause the increase of the number of redundant transmissions caused by hidden terminals. In this work, we seek the optimal value of the transmission range given a certain node density that results in a low energy consumption and maintains a reasonable high packet delivery ratio. Moreover, an appropriate choice of the transmission range reduces the busy terminal problem (Zhu et al. 2014) by limiting the burden on more stressed nodes from the network traffic.

SIMULATION EXPERIMENTS

In this section we address the problem of identifying the optimal transmission range of sensor nodes with respect to the energy cost of the network by resorting to the simulation model introduced in Section . Together with this optimization we also study the packet delivery ratio for the optimal transmission ranges. The packet delivery ratio is a good measure for observing the impact of the busy terminal especially for what concerns long transmission ranges.

Simulation scenarios and performance indices

We study UWSNs with various numbers of nodes deployed in a fixed space of $500m \times 500m \times 500m$ according to a uniform random distribution. The number of nodes varies from 100 to 800 and hence we recreate the scenarios that are similar to those that have been previously studied for other purposes in (Yan et al. 2008). The depth-threshold is 1/4 of the maximum transmission range, and the mobility pattern is a random walk. For MAC layer, we implement Broadcast MAC protocol (Mirza et al. 2009) which efficiently supports the functioning of flooding-based routing protocols. The

Parameter	Value
Network size	500m ×500m ×500m
Deployment	Random uniform
Initial energy of nodes	500J
Packet size	64 Bytes
Node mobility speed	2 m/s
Receiving power consumption	0.1 W
Idle power consumption	1 mW
Mobility pattern	Random walk
δ	Transmission range
f	3kHz

Table 1: Simulation Parameters

source node is placed in the bottom of the network. Multiple on-surface sinks have been deployed and the source node transmits a single packet after every two seconds. Table 1 summarizes the experiment setting.

In order to identify the optimal transmission range, we compute the following performance indices: (i) Energy cost of network defined as the expected energy required to successfully deliver a packet measured in Joule per packet, (ii) Packet delivery ratio and (iii) Total number of transmissions of network.

For each measurement we performed 20 independent experiments and build the confidence intervals at 95% whose width is always below 7% of the measured value.

Impact of transmission range on the energy cost of network, packet delivery ratio and total number of transmissions

In this experiment we study the network energy cost as function of the transmission range of the sensor.

Figure 2 shows the results of our experiments, i.e., the estimates of the energy cost of the network as a function of the transmission range for networks with 500 to 800 nodes. We observe that for very low transmission ranges the cost of retransmissions due to broken routes becomes prohibitive from the point of view of the energy consumed by the networks, whereas as the transmission range increases we have both to face the problem of the higher cost for the transmission of the single packet and the explosion of the number of retransmissions due to the hidden terminal problem and the consequent increased number of collisions. We can also observe that as the density of the nodes increases, the cost for redundant transmissions and the consequent collisions become dominant in increasing the energy cost of the network even in its optimal working point. For the four considered network densities we have an optimal transmission range of approximately 180 meters. We will see later on that above a certain density of nodes the optimal transmission range tend to stabilize to this value under the assumptions of Table 1.

Consulting Figure 3, the packet delivery ratio quickly

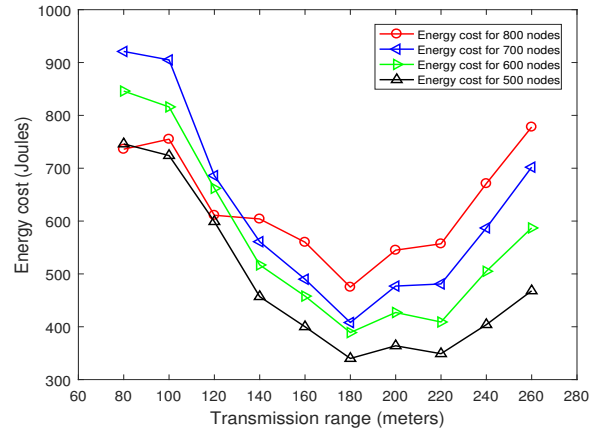


Figure 2: Energy cost of the network as a function of the transmission range.

increases with the sharp increase in the transmission range thanks to availability of multiple paths between source node and the sinks. However, after reaching at the maximum point, it declines due to the redundant transmissions and problems caused by the busy terminals. Interestingly, the transmission range associated with the optimal packet delivery ratio is coherent with the value which optimize the energy cost. It is also worth of notice that as observed in (Zhu et al. 2014) there is a strong correlation between high packet delivery ratio and reduction of the busy terminal problem. It is worthwhile of notice that the packet delivery ratios decrease after reaching the maximum but appear to become more stable. Also for what concerns the optimal packet delivery ratio, the experiments suggest that the networks with density of 500 nodes outperform those with higher densities in case of transmission ranges longer than 200 and this may suggest that finding the optimal densities could be an interesting problem for future works. Nevertheless, we should observe that a network with high node density tends to be more robust to failures and hence other performance indices should be analyzed before drawing conclusions.

Figure 4 shows the total number of transmissions performed in the network for 200s of simulation time. We can observe an initial increase of the amount of the transmissions due to the increased number of eligible forwarders of the sender nodes. However, this value tends to quickly stabilize although it shows an irregular pattern that probably depends on the average depth of the forwarding nodes.

Optimal transmission range as function of the node density

In order to experimentally study the connection between the optimal transmission range and the network node density we have run a large set of simulations for each

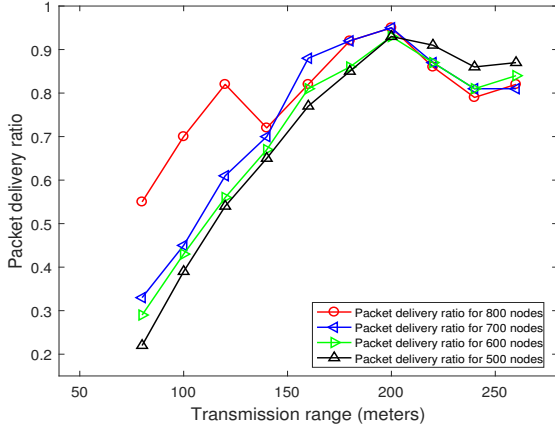


Figure 3: Packet delivery ratio with different node densities.

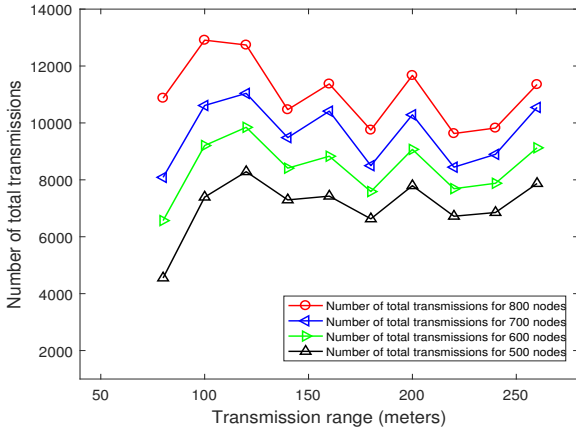


Figure 4: Total number of transmissions of network with different node density.

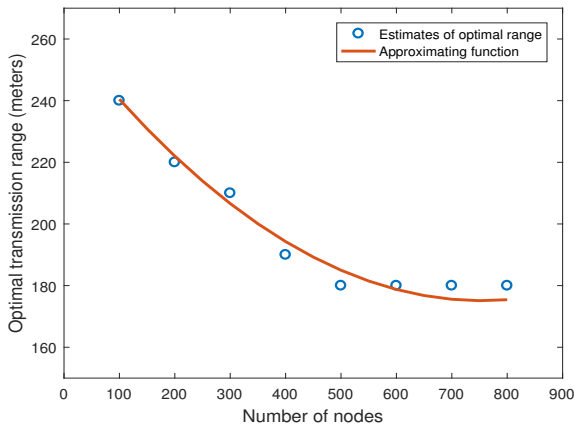


Figure 5: Optimal transmission range for different node densities with minimum energy cost.

given density and identified the optimal value for the energy cost. This has been done by assuming the convexity of the function $E_c = f(r)$, where E_c is the energy cost as function of the transmission radius r . Then we have proceeded by using a bisection method.

Figure 5 shows the optimal transmission range for various numbers of deployed nodes. We observe that for networks with a number of nodes higher than 500 the optimal transmission range stabilizes at approximately 180 meters. As observed in Section , this value optimizes both the network energy cost and its packet delivery ratio. As the number of deployed nodes decreases, the optimal transmission range increases to 240 meters associated with 100 nodes as number of intermediate forwarders decreases causing the decrease in total energy consumption of network.

According to our experiments if ρ is the network node density expressed in expected number of nodes for km^3 , we can say that the optimal transmission range r^* for DBR decreases with higher ρ as:

$$r^* \propto \rho^{1/6}.$$

In Figure 5 we plot the function $745/\rho^{1/6}$ and we can see that it provides a good approximation of the estimates of the optimal range. We observe that this result is quite different from the empiric law proposed in (Porto and Stojanovic 2007) for DACAP where the optimal transmission range was found to decrease with β as $1/\sqrt{\beta}$ where β is the 2-dimensional node density.

CONCLUSION

In this work we have studied the impact of the configuration of the nodes' physical layer parameters on the performance of DBR routing protocol. In particular, we have focused our attention to three performance indices: the network energy cost defined as the amount of energy spent by the network to successfully deliver a packet, the packet delivery ratio and the total number of transmissions in a simulation period of 200s. In order to reach our goal, a new simulator based on AquaSim-NG has been developed that with respect to its predecessors provides an accurate modelling of the modem operational modes, the cross-layer interactions required by this protocol and the busy terminal problem. The simulator can be downloaded at the official repository of AquaSim-NG (Martin 2016).

Specifically, we have addressed the problem of determining the optimal transmission range providing the lowest energy cost given the network density. To this aim we first studied the behavior of the energy cost as a function of the transmission range for networks with given node densities and empirically verified that this optimum value exists. Then, we have looked for this optimum value for different node densities. We observed that, according to our experiments, the transmission ranges that minimize the energy costs are also those that maximize the

packet delivery ratio. Finally, we studied the relation between the network density and the optimal transmission range. As expected, we found that sparse networks require higher optimal transmission ranges, but that this values tends to decrease slowly with denser networks. From the experiments that we run, we observed that the optimal transmission range decreases as $1/\rho^{1/6}$ where ρ is the expected number of nodes for km^3 . Future works include the development of an analytical model to validate this empirical law.

We believe that the outcomes of this work, combined with the previously developed optimizations at the network layer studied in (Yan et al. 2008), can be helpful in the optimization of the power consumption in UWSNs adopting DBR routing protocol.

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