Energy Efficient Routing for Multi-hop Underwater Acoustic Networks

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Abstract
The goal of this paper is to establish the optimal routing path that minimizes the total energy consumption for a given target signal-to-noise ratio (SNR) for a 2-dimensional multi-hop underwater acoustic network. The energy efficient routing paths for both variable transmission power (VTP) and fixed transmission power (FTP) schemes were investigated. An empirical closed-form expression of the optimal frequency-distance relationship was derived as an effective way to simplify the calculation. It was shown that the total energy consumption of the network is minimized only if all the hop distances are equal for a linear multi-hop network for both VTP and FTP sceneries. In the case of equispaced relays, the analytical results on the optimal number of hops that minimizes the total energy consumption and the optimal total energy consumption of the network were also provided. The results may provide theoretic foundation for the establishment of nearshore resource monitoring system.

Keywords: *Energy Efficient Routing, Multi-Hop Underwater Network, Linear Equidistant Network, AN Product.*

1. Introduction

Underwater acoustic networks (UWANets) have attracted increasing attentions recently for the potential applications in oceanographic data collection, aquatic resource monitoring, disaster prevention, and distributed tactical surveillance [1-3]. Usually the nodes are battery-powered and operate unattended for relatively long periods of time, but existing underwater recharge technics are immature, and replacing batteries on up to hundreds of nodes undersea is infeasible, so energy efficient communication techniques are essential for unlocking the potential of UWANets.

Several energy-efficient routing protocols [4-6] and media access control (MAC) protocols [7, 8] for UWANets have been proposed to reduce the network energy consumption, dealing with the long delays or the reliability, but they have not taken into account the propagation characteristics of the underwater acoustic signals and few of them consider a multi-hop strategy.

Multi-hop is supposed to be a promising strategy for next-generation UWANets. The most distinguishing property of acoustic channels is the fact that the path loss underwater increases not only with propagation distance but also with signal frequency, so shorter distance offers less transmission power and more favorable bandwidth [9-11].

Current studies dealing with the energy or transmission power in multi-hop UWANets often favor a linear equidistant network model, as such a model, though simple, may capture some of the essential elements [11-13]. Though in [11] it is pointed out that this kind of model is more energy saving than two-dimensional models with randomly placed nodes, it does not provide theoretical proof. Similar problems in terrestrial multi-hop networks have been well studied. In [14] it has been proved that the minimum total energy consumption for AWGN channel is achieved by a regular linear network and in [15, 16] that total energy consumption is minimized if and only if all the hop distances are equal for linear multi-hop networks.

From another perspective, to get in-depth knowledge of energy consumption of UWANets, it is also essential to understand the power-distance relationship (for a target signal-to-noise ratio (SNR) the required transmission power as a function of the transmitter- receiver distance), as well as the optimal frequency-distance relationship (the optimal frequency that corresponds to the best attenuation/ noise combination as a function of the link distance) [17]. Though in [17] an empirical closed-form approximation for the power-distance relationship was proposed, the counterpart for the optimal frequency-distance relationship is still unclear, which may be an effective way to simplify the calculation if each node is assumed to choose the optimal frequency as its signal frequency.

The goal of the present paper is to address the following question: For a multi-hop UWANet with arbitrarily distributed relays in a 2-dimensional plane, what is the optimal routing path that minimizes the total energy consumption for a given target SNR? We investigate the energy efficient routing path for 2-dimensional multi-hop underwater acoustic networks for two schemes: variable transmission power (VTP) and fixed transmission power (FTP) modes. An empirical closed-form expression of the optimal frequency-distance relationship is derived as an effective way to simplify the calculation if each node is assumed to choose the optimal frequency as its signal frequency. We prove that the total energy consumption of the network is minimized only if all the hop distances are equal for a linear multi-hop network, for both VTP and FTP scenery. The analytical results on the optimal number of hops and the optimal total energy consumption of the linear equidistant network are also provided.

The remainder of this paper is organized as follows. In Section 2, the system model is established. In Section 3, the empirical closed-form expression for the optimal frequency-distance relationship is derived. The minimum energy routing paths for both VTP and FTP sceneries are worked out in Section 4. Numerous results are demonstrated in Section 5, and some conclusion remarks are discussed in Section 6.

2. System Model

In this section, we describe the system model, including underwater acoustic attenuation and noise model, the 2-dimensional multi-hop network model and the energy model.

2.1. Underwater Acoustic Attenuation and Noise

An underwater acoustic channel is characterized by an attenuation experienced by a signal of frequency f in kHz traveling over a distance d in km as[1] [18]

$$10\log A(d,f)=\kappa\cdot 10\log(\frac{d}{d_{ref}})+d\cdot 10\log\alpha(f) \quad (1)$$

where d_{ref} is a reference distance (typically 1 m), κ denotes the spreading factor that describes the geometry of propagation (typically $1\le\kappa\le 2$), and $\alpha(f)$ is the frequency dependent absorption coefficient, which is an increasing function of f and can be obtained using Thorp's formula [19] for frequencies above a few hundred Hz. For lower frequencies, the following empirical formula may be used [17]

$$10\log\alpha(f)=0.11\frac{f^2}{1+f^2}+0.011f^2+0.002 \quad (2)$$

The overall power spectral density of the ambient noise underwater $N(f)$ is affected by four sources: turbulence, shipping, waves, and thermal noise. In a certain frequency region, the following practical approximation can be used [17]

$$10\log N(f)=N_0-\eta\log f \quad (3)$$

With $N_0=50$ dB re μPa and $\eta=18$ dB / *decade* .

Note that we assume in our work the spreading factor $\kappa=1.5$; $\alpha(f)$ and $N(f)$ are calculated according to Eq. (2) and Eq. (3), respectively.

2.2. Multi-hop Network Model

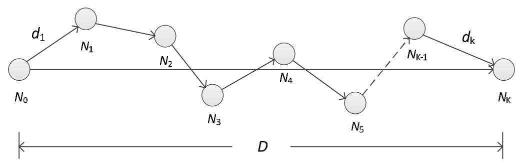

Fig. 1 A 2-dimensional multi-hop network model

The 2-dimensional multi-hop network under consideration is illustrated in Figure 1, where a pair of source and destination terminals separated by a distance D communicate with each other by routing their data through $K-1$ intermediate relay terminals, spaced arbitrarily between the source-destination pair. The source terminal is identified as N_0 , the destination terminal is identified as N_K and the intermediate terminals are identified as N_i, $i=1,...,K-1$, where K is the number of hops along the transmission path. We denote as in [20] the relay distance of hop i as d_i given by $d_i=\varphi_i D$, and it is obvious $\sum_{i=1}^{K}\varphi_i\ge 1$ (note $\sum_{i=1}^{K}\varphi_i=1$ denotes a linear path).

The following assumptions are made throughout this paper. (1) Every node can only operate in half-duplex, so that it is incapable of simultaneous transmission and reception. (2) Link connectivity is only considered between intermediate neighboring relays, i.e., no cooperative relaying scheme is exploited. (3) The network operates without spatial reuse, so that inter-link interference is not considered. (4) Every node may choose a FTP or VTP mode (in VTP mode the node can vary its transmission power continuously), and no peak power constraint is imposed.

2.3. Energy Model

The energy consumption for transmitting one packet one time of one node can be modeled as

$$E=E_t+E_c \quad (4)$$

[1] In this paper, "log" is used to denote logarithm of base 10 and "ln" is used to denote logarithm of base e.

Table I Parameters of the close-form approximation for the optimal frequency

General model	*Coefficients*	*Goodness of fit*
$f_o(d) = \alpha d^{\beta}$	a = 18.89, β = -0.5012	SSE: 1.2946, RMSE: 0.1642
$f_o(d) = \alpha d^{\beta} + \chi$	a = 19.12, β = -0.4962, χ = -0.2796	SSE: 0.8086, RMSE: 0.1274

where E_t is the transmission energy consumption and E_c is the received and processing energy consumption.

The transmission energy E_t can be calculated as the transmission power P_t times the transmission time of the packet $T = \frac{L}{\rho B(d)}$, where L is the packet size in bits, ρ is the bandwidth efficiency of the modulation in bps/Hz, and $B(d)$ is the available bandwidth depending on the link distance [11].

For a given SNR requirement, the transmission energy consumption associated to a distance d and available frequency f can be expressed as

$$E_t = \xi \cdot P_t \cdot T = \frac{\xi L}{\rho} A(d,f) N(f) \gamma_{tgt} \quad (5)$$

where ξ is the conversion factor from acoustic power in dB re μPa to electrical power in Watt (which depends on the efficiency of the electronic circuitry), and $\gamma_{tgt} = \frac{P_t / A(d,f)}{N(f)B(d)}$ is the target received SNR.

The received and processing energy E_c is independent with link distance and is usually much more smaller than E_t. So in our analysis, E_c is assumed to be constant, and therefore the total energy consumption for a single link is

$$E = E_t + E_c = \frac{\xi L}{\rho} A(d,f) N(f) \gamma_{tgt} + E_c \quad (6)$$

3. Simplification of AN Product

As can be seen in Eq. (6), the total energy consumption, which depends on the AN product, $A(d,f)N(f)$, involves two variables (d and f), and thus is rather complicated. So in this section, we investigate the properties of the AN product and derive an empirical closed-form expression of the optimal frequency-distance relationship as an effective way to simplify the calculation.

3.1. Properties of AN Product

The AN product has been preliminary studied in [17]. Here we review two useful properties of AN product and provide their brief proofs.

Consider the AN product expressed in the form of decibels:

$$AN_{\mathrm{dB}} = \kappa 10 \log d + 0.11 \frac{f^2 d}{1+f^2} + 0.011 f^2 d + 0.002d - 18 \log f + 30\kappa + 50 \quad (7)$$

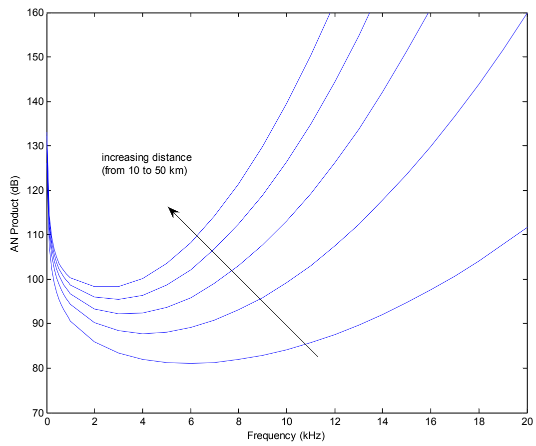

Fig. 2 AN product vs. frequency for different distances

The AN product vs. frequency for distances from 10 km to 50 km is described in Figure 2, which features the following properties of AN product.

Property 3.1 *AN product is a monotonically increasing function of internode distance d.*

Proof: We begin by differentiating AN_{dB} with respect to d, and obtain the first-order derivative

$$\frac{\partial AN_{\mathrm{dB}}}{\partial d} = \frac{\kappa 10}{d \ln 10} + 0.11 \frac{f^2}{1+f^2} + 0.011 f^2 + 0.002 > 0 \quad (8)$$

Therefore, the AN product is a monotonically increasing function of internode distance d. □

Property 3.2 *For a given transmission distance d, there exists an optimal frequency $f_o(d)$ which minimizes AN product, i.e.,*

IJCSI International Journal of Computer Science Issues, Vol. 9, Issue 6, No 1, November 2012
ISSN (Online): 1694-0814
www.IJCSI.org

$$f_o(d) = \arg\ \min A(d,f)N(f) \qquad (9)$$

Proof: We begin by differentiating AN_{dB} with respect to f, and find for the first-order derivative,

$$\lim_{f\to 0^+}\frac{\partial AN_{\mathrm{dB}}}{\partial f} < 0 \quad \text{and} \quad \lim_{f\to +\infty}\frac{\partial AN_{\mathrm{dB}}}{\partial f} > 0 \qquad (10)$$

so there exists an frequency $f_o(d)$ and such that

$$\left.\frac{\partial AN_{\mathrm{dB}}}{\partial f}\right|_{f=f_o(d)} = 0 \qquad (11)$$

So it is clear that $f_o(d)$ can reach the minimal AN product. □

***Remark*:** The relationship between $f_o(d)$ and d may lead to a simplification of calculating AN product from two variables f and d to only one variable d.

3.2. Relationship between d and $f_o(d)$

To obtain the relationship between d and $f_o(d)$, we differentiate AN_{dB} with respect to f, and set the first-order derivative equals to zero,

$$\frac{\partial AN_{\mathrm{dB}}}{\partial f} = \left.\frac{0.22df}{(1+f^2)^2} + 0.022df - \frac{18}{f\ln 10}\right|_{f=f_o(d)} = 0 \qquad (12)$$

and get

$$d = \left.\frac{9000(1+f^2)^2}{11\ln 10(f^6+2f^4+11f^2)}\right|_{f=f_o(d)} \qquad (13)$$

However, we can only attain a closed-form solution for node distance as a function of optimal frequency from Eq. (13), but not vice versa. A closer examination of the numerical results reveals that the optimal frequency decays almost linearly with internode distance on a logarithmic scale. Hence we use curve fitting methods to obtain such approximations of two general models, $f_o(d) = ad^{\beta}$ and $f_o(d) = ad^{\beta} + \chi$, the parameters of which are shown in Table 1 with their goodness of fit in terms of the sum of squares due to error (SSE) and the root mean squared error (RMSE).

As shown in Eq. (13), $f_o(d)$ is in the form of even power (square, biquadrate, etc.) while the parameter β of the closed-form expressions nearly equals to -0.5, which enables us to simplify our calculations, so we finally choose the closed-form approximation as

$$f_o(d) = 19d^{-0.5} \qquad (14)$$

with its SSE 2.6207 and RMSE 0.2196.

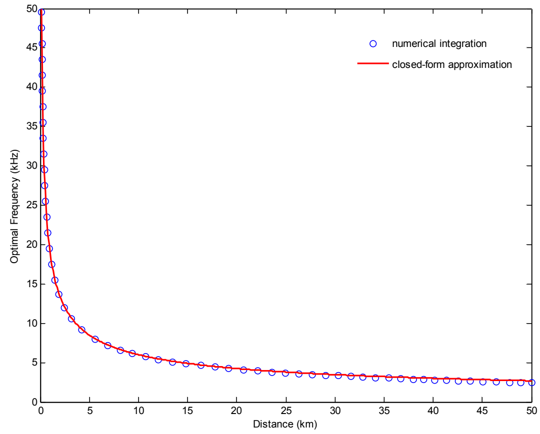

Fig. 3 Optimal frequency vs. distance

The empirical closed-form approximation of optimal frequency-distance relationship is illustrated in Figure 3 (solid curve), exhibiting good agreement with numerical results (circles).

3.3. Approximation of AN Product

We assume that if the node distance is d, each node will choose the optimal frequency $f_o(d)$ as the acoustic signal frequency. Substituting f in Eq. (7) by $f_o(d)$ in Eq. (14), we can get

$$AN(d) = 10^{g(d)} \qquad (15)$$

where

$$g(d) = (\kappa+0.9)\log d + 0.0002d + \frac{0.03971d}{d+361} + 3\kappa - 1.8\log 19 + 5.3971$$

Note $g(d)$ is a monotonically increasing function as $g'(d) > 0$.

4. Minimum Energy Routing Analysis

In this section, we use the approximation of AN product to analyze the minimum energy routing for two practical transmission power strategies, namely variable transmission power strategy (VTP) and fixed transmission power strategy (FTP).

Variable transmission power: In this scenario, each node adjusts its transmission power for a link so that the signal reaches the destination node with the same target received SNR. And it is clear that links with larger hop distances require higher transmission power than those with smaller distances when their available bandwidth varies slightly, and this leads to the fundamental gain in energy efficiency for the network.

Fixed transmission power: In this mode, each node chooses the transmission power to be a fixed constant, which depends on the link whose attenuation/noise combination (AN product) is the largest among all links, so as to guarantee that the received SNR for each link is no less than the target SNR. There will be no gain in terms of energy efficiency since links with smaller distances have to pay for the loss in energy due to the forced same transmission power for every relaying link. Note though such an approach is obviously inefficient, it represents some current acoustic transducers that do not provide the mechanism of dynamic power adjustment.

4.1. Minimum Energy Routing for VTP

The energy consumption of link i can be obtained from Eq. (6) as

$$E_i = E_{t,i} + E_c = \frac{\xi L_i}{\rho} A(d_i, f_i) N(f_i) \gamma_{r,i} + E_c \quad (16)$$

As the target SNR is assumed to be the same for each link, i.e. $\gamma_{r,i} = \gamma_{tgt}$, the total energy consumption of the network for VTP then is

$$E_{total} = \sum_{i=1}^{K} (E_{t,i} + E_c) = \frac{\xi L \gamma_{tgt}}{\rho} \sum_{i=1}^{K} A(d_i, f_i) N(f_i) + K E_c \quad (17)$$

With simplified AN product in Eq. (15), the general problem of minimizing total energy consumption can be formulated as the following optimization problem,

$$\begin{aligned} \min_{d_1,\ldots,d_K} \quad & E_{total} = \frac{\xi L \gamma_{tgt}}{\rho} \sum_{i=1}^{K} 10^{g(d_i)} + K E_c \\ s.\,t. \quad & \sum_{i=1}^{K} d_i \geq D \end{aligned} \quad (18)$$

where the optimization variable is d_i. The solution to this problem can be obtained from following theorem.

Theorem 4.1 *For a multi-hop UWANet with K hops arbitrarily placed between a source-destination pair, where each node chooses the VTP mode, the minimum total energy consumption for a target SNR is achieved by a linear equidistant network.*

Proof: First, we declare that the function $\mathrm{X}(d) = 10^{g(d)} \cdot g'(d)$ is monotonically increasing with d, in that $\mathrm{X}'(d) > 0$.

Then we can prove the optimality using the Lagrangian function of

$$L(\boldsymbol{d}, \lambda) = \frac{\xi L \gamma_{tgt}}{\rho} \sum_{i=1}^{K} 10^{g(d_i)} + K E_c - \lambda \left(\sum_{i=1}^{K} d_i - D \right) \quad (19)$$

where $\lambda \geq 0$, and $\boldsymbol{d} = (d_1, d_2, \ldots, d_K)$. Therefore, the Karush-Kuhn-Tucker (KKT) conditions are given as

$$\begin{aligned} & \ln 10 \cdot \frac{\xi L \gamma_{tgt}}{\rho} \cdot 10^{g(d_i)} \cdot g'(d_i) - \lambda = 0, \quad \forall i \\ & \lambda \cdot \left(\sum_{i=1}^{K} d_i - D \right) = 0 \end{aligned} \quad (20)$$

From the first group of optimality condition we can derive that $\lambda \neq 0$ and $d_1 = d_2 = \cdots = d_K$ (from the monotonicity of $\mathrm{X}(d)$), which represents an equidistant network; from the last optimality condition, $\lambda \neq 0$ results in $\sum_{i=1}^{K} d_i = D$, which denotes a linear multi-hop network. Though local optima, it is also the global solution as $\sum_{i=1}^{K} 10^{g(d_i)}$ is monotonically increasing. Thus, Theorem 4.1 is confirmed. □

4.2. Minimum Energy Routing for FTP

The minimum transmission power of FTP is chosen to ensure the target SNR for every link, so the energy consumption of link i depending on the link with largest AN product is

$$E_i = E_{t,i} + E_c = \frac{\xi L \gamma_{tgt}}{\rho} A(d_i, f_i) N(f_i) \Big|_{\substack{d_i = d_{max} \\ f_i = f_o(d_{max})}} + E_c \quad (21)$$

and thus the total energy consumption of the network for FTP is

$$\begin{aligned} E_{total,FTP} &= \sum_{i=1}^{K} (E_{t,i} + E_c) \\ &= K \left(\frac{\xi L \gamma_{tgt}}{\rho} A(d_i, f_i) N(f_i) \Big|_{\substack{d_i = d_{max} \\ f_i = f_o(d_{max})}} + E_c \right) \end{aligned} \quad (22)$$

Therefore the problem of minimizing the total energy consumption for FTP can be written with simplified AN product in Eq. (15) as

$$\min_{d_{max}} \quad E_{total,FTP} = K \left(\frac{\xi L \gamma_{tgt}}{\rho} 10^{g(d_{max})} + E_c \right) \quad (23)$$

where the optimization variable is $d_{\max}$. This problem can be solved from following theorem.

Theorem 4.2 *For a multi-hop UWANet with K hops randomly distributed between a source- destination pair, where each node chooses the FTP mode, the minimum total energy consumption is achieved by a linear equispaced network.*

Proof: Obviously, $E_{total,FTP}$ is monotonically increasing with $d_{\max}$, so Eq. (23) can be converted into the following equivalent problem.

$$\min \quad d_{max} \quad (24)$$

As $d_i \le d_{max}$, it is clear $\sum_{i=1}^{K} d_i \le K d_{max}$; while $\sum_{i=1}^{K} d_i \ge D$, so $K d_{max} \ge D$. Thus $d_{max} \ge \frac{D}{K}$, i.e.

$$\frac{D}{K} = \arg\ \min d_{max} \tag{25}$$

which denotes a linear equidistant network. Therefore, Theorem 4.2 is achieved. □

4.3. Optimization of the number of Hops

The theorems above conclude that the linear equidistant model is most energy saving, and the question of what the optimal distance or optimal number of hops naturally arises. So we consider the total energy consumption

$$E_{total} = \sum_{i=1}^{K} (E_t + E_c) = K(\frac{\xi L \gamma_{tgt}}{\rho} 10^{g(\frac{D}{K})} + E_c) \tag{26}$$

Differentiating the term with respect to K (treating K as a continuous random variable), and setting the derivative to zero, we can obtain such relation as

$$10^{g(\frac{D}{K})} (\ln 10 \frac{D}{K} g'(\frac{D}{K}) - 1) = \frac{\rho E_c}{\xi L \gamma_{tgt}} \tag{27}$$

Let d^* be the solution to

$$10^{g(d)} (\ln 10 d g'(d) - 1) = \frac{\rho E_c}{\xi L \gamma_{tgt}} \tag{28}$$

then the optimal number of hops that minimizes the total energy consumption is

$$k^* = \frac{D}{d^*} \tag{29}$$

The minimum of the total energy consumption at the optimal number of hops is thus given by

$$E_{total,k^*} = k^* (\frac{\xi L \gamma_{tgt}}{\rho} 10^{g(\frac{D}{k^*})} + E_c) \tag{30}$$

which shows that the optimal number of hops depends on the transmission time of the packet, the received and processing energy, the end-to-end distance, and the spread factor.

5. Numerical Results

In the numerical results, we assume that the bandwidth efficiency of the modulation $\rho = 0.5$,the conversion factor $\xi = 4 \times 10^{-17}$, the packet size L =256 bytes, and the received and processing energy consumption of each node E_c =0.5 J unless otherwise specified. Hereafter we only consider the linear network (i.e. $\sum_{i=1}^{K} \varphi_i = 1$), since the energy consumed by nonlinear relays apparently stands at a higher level.

In Figure 4 and Figure 5, we plot the total energy consumption versus distance when $\gamma_{tgt} = 20$ dB with single hop ($k = 1$) and multi-hop ($k = 2, 3$) for selected location of relays. We can see that the total energy consumption for both the VTP and FTP strategies rises with increasing distance, and goes up even faster for longer distances. This is mainly caused by the property of attenuation/noise combination. Moreover, the relays of FTP take more energy consumptions than that of VTP under the same network topology, which is consistent with what has discussed above, as FTP scheme has to take extra energy to keep a state of constant transmission power of every node. Besides, in the drawings of partial enlargement, we notice that multi-hop may not ideal solution for energy saving when the end to end distance is relatively short (e.g. distances below 15 km), as the energy consumed by the introducing relays outweighs the energy they saved at short distance.

Figure 6 illustrates the total energy consumption versus the number of hops for distances from 10 km to 100 km when $\gamma_{tgt} = 20$ dB, and it clearly shows the existence of an optimal number of hops to use over a given link distance. The total energy consumption decreases sharply as the number of hops increases before it reaches the optimal number of hops, and increases slowly afterwards. It also shows that the longer distance, the more energy it consumes.

Figure 7 demonstrates the total energy consumption versus distance for different numbers of hops when $\gamma_{tgt} = 20$ dB. It is shown that the points of intersection of contiguous curves (pink circle), representing one hop increasing of the optimal number of hops, are almost in a straight line. This is fit to the theoretical expectation in Eq. (29), but it is not a strict line in that k^* is an integer, leading minor deviation.

To observe how target SNR can affect the energy consumption, we plot the total energy consumption versus 1) distance with different for given number of hops ($k = 3$) and 2) the number of hops with different γ_{tgt} at given distance ($D = 50$ km) in Figure 8 and Figure 9 when γ_{tgt} is varied. It is observed that higher target SNR leads to more energy consumptions, but has similar variation trend. And this also offers a reference of how the curves in Figure 4 to Figure 7 will change when γ_{tgt} is varied.

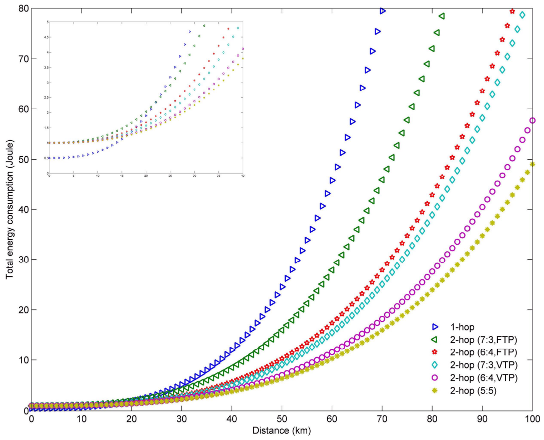

Fig. 4 E_{total} vs. distance when $\gamma_{tgt} = 20$ dB with single hop ($k=1$) and multi-hop ($k=2$) for linear selected location of relays, $\varphi_1 : \varphi_2 = 7:3, 6:4, 5:5$

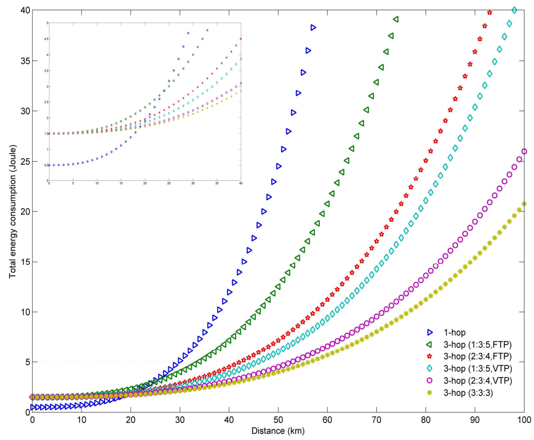

Fig. 5 E_{total} vs. distance when $\gamma_{tgt} = 20$ dB with single hop ($k=1$) and multi-hop ($k=3$) for linear selected location of relays, $\varphi_1 : \varphi_2 : \varphi_3 = 1:3:5, 2:4:6, 3:3:3$

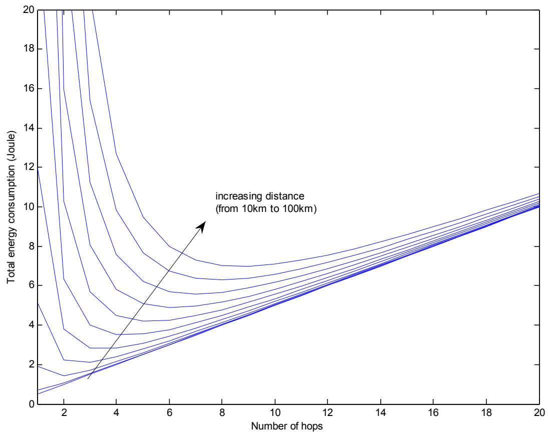

Fig. 6 E_{total} vs. number of hops when $\gamma_{tgt} = 20$ dB with different distances for linear equispaced relays

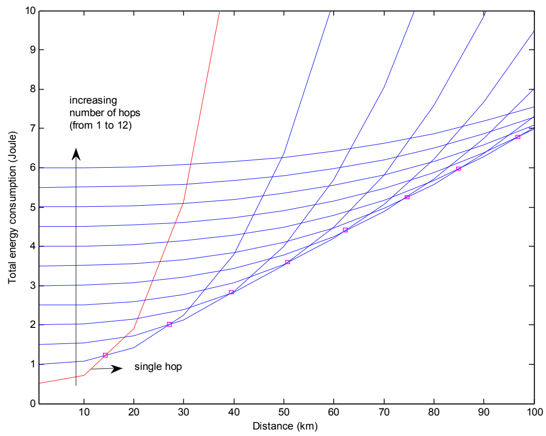

Fig. 7 E_{total} vs. distance when $\gamma_{tgt} = 20$ dB with different numbers of hops for linear equispaced relays

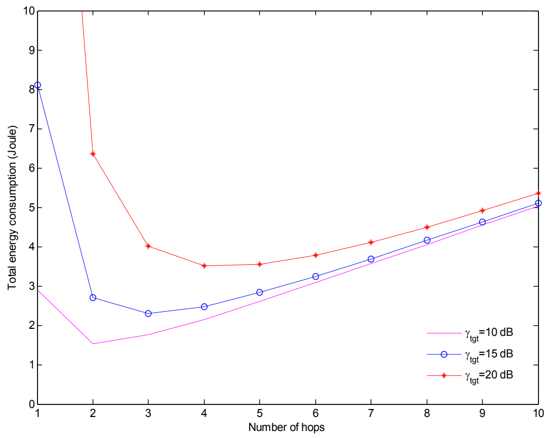

Fig. 8 E_{total} vs. number of hops with different γ_{tgt} at $D = 50$ km for linear equispaced relays

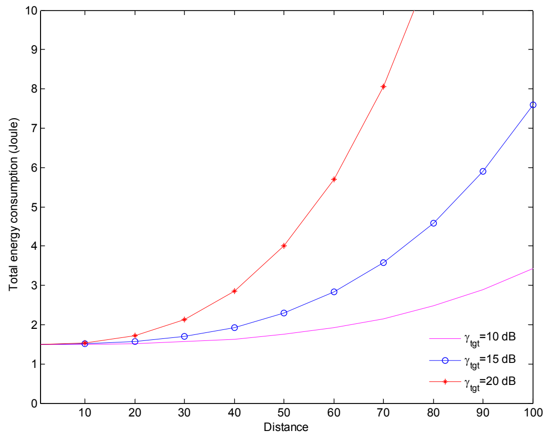

Fig. 9 E_{total} vs. distance with different γ_{tgt} for multi-hop ($k=3$), linear equispaced relays

6. Conclusions

The main contributions of this paper are as follows. 1) We prove that for a multi-hop UWANet with K hops arbitrarily placed between a source-destination pair, the minimum total energy consumption for a target SNR is achieved by a linear equidistant network, for both FTP and VTP schemes. 2) We obtain an empirical closed-form expression of the optimal frequency- distance relationship as an effective way to simplify the calculation as we assume that each node chooses the optimal frequency as its signal frequency. 3) We present analytical results on the optimal number of hops and the optimal total energy consumption of the linear equidistant network. These results herein may provide theoretic foundation for the establishment of nearshore resource monitoring system.

Our future research includes considerations of the spatial reuse and reliable communications in the link. Also, extending the theoretical results to 2-dimensional nonlinear networks would be more valuable to practical applications.

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