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RF channel modelling and multi-hop routing for wireless sensor networks located on oil rigs

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Abstract: This study presents a combined analytical and empirical model for predicting the signal loss effects of metallic drilling rig structures on radio-frequency electromagnetic waves used by wireless sensor networks (WSNs) installed on a drilling rig. The model is based on the combination of free space path loss and the excess loss caused by the metallic structure separately. The authors combine both losses to predict the overall loss of signal strength. The model has been validated against field data collected from multiple drilling rigs. Further modification of the model to include the effects of different signal frequencies is under way. They present simulation results from OMNeT++ based on their model, to establish the packet loss and energy consumption expected for a real WSN. They also present a novel dynamic multi-hop routing protocol, which improves network performance by removing the constraints of single-hop forwarding. The algorithm directs packets to their destination via a selected node within a routing 'cluster'. By combining their channel model and routing protocol, they are able to achieve 100% packet success, while setting transmit power levels appropriately to achieve the longest possible network lifetime.

1 Introduction

Wireless communication is an extremely vibrant area. Since the 1960s when wireless communications became an area of interest, there has been a surge of improvements, research activities, and novelties to address many challenges. The tremendous advances in wireless have been achieved due to several factors including explosive growth in demand for seamless connections, and the intense progressive trend of very large-scale integration technology enabling the complex system designs required [1].

Wireless communications have captured the attention of all industries owing to its unique feature of providing connectivity along with mobility, in contrast to traditional wired communication networks. Furthermore, wireless communication systems offer cost and maintenance advantages when compared with wired networks. As a result, almost all industries try to take advantage of wireless communication networks for systems such as wireless sensor networks (WSNs), remote control, and gas/pressure/volume sensing. Exploiting wireless communication systems means we have to confront two major problems: namely, fading and interference. Fading is due to the time variation of channel strength due to the small-scale effect of multipath fading, as well as larger-scale effects such as path loss via disturbance attenuation and shadowing by obstacles. Interference is caused by the presence of other wireless users communicating over the same medium.

Petroleum exploration and extraction is one of the industries where wireless communications are used intensely. Petroleum extraction from a reservoir is a two-step process. The first step is to drill a wellbore to the underground reservoir. The next step is to extract the oil through the wellbore. During both of these steps, providing a safe working environment for the worker is of utmost importance. Drilling is considered a hazardous activity due to the possibility of fire or explosion, as well as exposure to toxic gases such as hydrogen sulphide. Monitoring is necessary to ensure that all operations are carried out safely, and to ensure the structural and mechanical integrity of the drilling rig.

Monitoring data are collected during both drilling and extraction. During the drilling phase, monitoring data are collected from the wellbore, as well as from the machinery on the rig, to continually assess their structural and mechanical state. For data collection purposes, sensor nodes (SNs) – either wired or wireless – are placed at different positions on the drilling equipment and within the wellbore and reservoir. On average, a drilling rig moves from one place to another every month. This movement poses challenges to the maintenance of wiring needed for wired sensor networks. As a result, wireless data gathering from locations throughout the rig is a very attractive option. In this approach, the SNs are then collected together and operate as a WSN.

WSNs are widely used in many applications [2–5]. Many important aspects of WSNs have been studied such as optimal node placement [6], accurate localisation services [7], coping with node mobility [8], and conservation of the limited energy reserves of wireless nodes [9]. Signal transmission is one of the primary sources of energy consumption in WSNs [10]. By analysing the wireless channel properties on a drilling rig, the required level of transmission power can be predicted for successful data collection. This analysis can help to save energy by setting transmitters to lower radiated power, and to accurately predict network lifetime. A complicating factor is the metallic structure of a drilling rig, which can have a significant impact on the wireless channel, and thus the power levels required. However, this topic has not received much attention.

Many papers available in the literature report the behaviour of the wireless channel in the case of underground mining. For example, an analysis of a terahertz channel through oil reservoirs has been presented in [11]. Spreading of wireless signals through soil and crude oil/water mixtures has been analysed in this paper. Research challenges involved in underground deployment of WSNs have also been discussed in [12]. Many other papers [13–17] explore the issues of deployment and operation of WSNs in underground mining.

All of these aforementioned works deal with wireless transmission through an underground reservoir, or body, while having a great knowledge of the transmission channel helps the performance of the WSNs, specifically in the drilling rig environment. There is very little work that analyses the wireless channel above ground, on drilling rigs. In this paper, we present a model that predicts the attenuation of a signal between WSN nodes at known locations on a drilling rig. The proposed model determines the excess loss of signal strength caused by the metallic structure of the rig, and combines it with FSL to compute the total signal attenuation. We validate the model with field data collected from multiple drilling rigs.

2 Theoretical background

A good understanding of the wireless channel, its key physical parameters, and the modelling issues, lays the foundation for wireless system dimensioning and planning. In fact, in wireless systems it is critical to obtain an accurate channel model to describe the underlying wireless propagation environment due to its considerable effect on system performance. A good channel model enables the prediction of received signal power as a function of transmitted power, frequency, distance, and impairments. Wireless channels operate through electromagnetic radiation from the transmitter to the receiver. In principle, one could solve the electromagnetic field equations, using the characteristics of the transmitted signal, to find the electromagnetic field impinging on the receive antenna. For this purpose, the obstructions caused by ground, buildings, vehicles etc. in the path of this electromagnetic wave must be taken into account.

However, in realistic scenarios, reliable prediction of the received signal by solving the wave equations is highly complex owing to the various propagation mechanisms possible in the environment. These mechanisms, emphasising those aspects of the problem relevant for wireless communications, are reflection, diffraction, and scattering. Owing to the presence of such phenomena, many characteristics of the transmit signal such as amplitude, phase, time of arrival, angle of arrival, and polarisation will change over the path (or paths) from the transmitter to the receiver [18].

Propagation models can also be classified into three groups depending on how they are derived. From this view, we can have empirical, physical, and analytical models. Empirical models are based on extensive measurement campaigns, and are usually suitable for, and applicable to, macrocellular environments such as open areas, suburban, urban, and rural areas because the propagation behaviour is mainly defined by land use; neither reflection nor diffraction need to be taken into account. However, such models must be tuned for use in specific environments. In contrast, physical models can be used in general settings because they provide physical insight into the actual propagation mechanisms. Physical models are typically based on the physical optics and geometry of the obstructions. This makes physical models appropriate for microcellular environments. Analytical models can be classified as either solving the electromagnetic wave equations numerically, or applying optical ray tracing methods with some diffraction method. Analytical models are relatively complex, in contrast with empirical and physical models. In this paper, we use an empirical model [19].

To examine the data we collected on real drilling rigs, we have compared our proposed model with three other commonly used path loss models. These are free space path loss (FSL), path loss with shadowing, and path loss predicted from transceiver parameters. We also exploited the MATLAB curve fitting toolbox that interactively fits a curve by using linear or non-linear regression models. In the following, these models will be mathematically described.

The simplest possible scenario, and our first model for comparison, is when the wireless transmission is being established in free space along an line-of-sight (LOS) path between the transmitter and the receiver. If the transmit antenna is radiating isotropically over a sphere of radius R, the *Friis* transmission formula for FSL can be derived [20]

$$\frac{P_\mathrm{r}}{P_\mathrm{t}} = G_\mathrm{t} G_\mathrm{r} \left(\frac{\lambda}{4\pi R} \right)^2 \tag{1}$$

where P_t and P_r are transmit and received powers and G_t and G_r are the transmit and receive antenna gains, respectively. λ is the wavelength of the signal. Using the Friis transmission formula, the FSL is

$$L_{\mathrm{FSL}} = \frac{P_\mathrm{t} G_\mathrm{t} G_\mathrm{r}}{P_\mathrm{r}} = \left(\frac{4\pi R f}{c} \right)^2. \tag{2}$$

For the sake of simplicity, the same formula can be expressed in decibels in (3), where distance R and frequency f are in kilometres

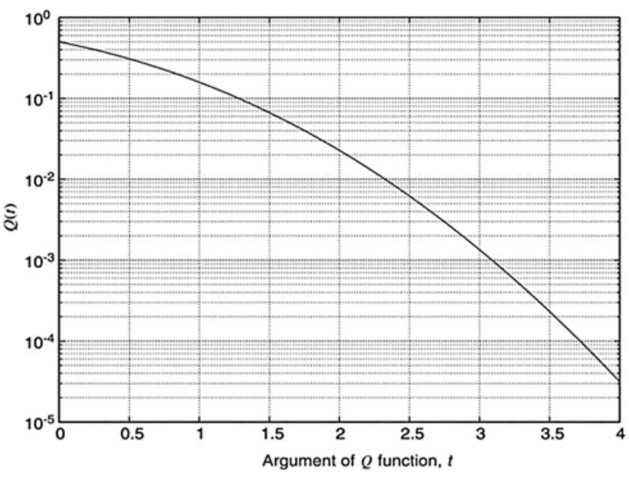

Fig. 1 *Q-function graph*

Fig. 2 *Example Libelium–Waspmote*

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Fig. 3 *Drilling rig number one*

Fig. 4 *Drilling rig number two*

and megahertz, respectively, and speed of light c is 3×10^8 m/s

$$L_{\mathrm{FSL}}(\mathrm{dB}) = 32.4 + 20\log_{10}(R) + 20\log_{10}(f). \tag{3}$$

For our second comparison, we use an empirical path loss with shadowing model composed of two terms [21]. The first term is similar to the Friis FSL and the second is a shadowing fading component that stems from the obstructions caused by objects in the signal path. The total path loss is the sum of the two components

$$L_{\mathrm{total}} = L_{\mathrm{FSL}} + L_{\mathrm{shadowing}}. \tag{4}$$

Here, $L_{\mathrm{shadowing}}$ is a zero-mean Gaussian random variable with standard deviation σ. To calculate $L_{\mathrm{shadowing}}$, we find the value of $t = z/\sigma$ for which the path loss is less than the maximum allowable value for at least 98% of the locations of interest

$$Q(t) = 2\% = 0.02. \tag{5}$$

Using the Q-function graph, as shown in Fig. 1, we can find the value of t. By multiplying t and the standard deviation σ of the shadowing fading component, the shadowing loss can be found. We note that this method can be tuned to the characteristics of an actual environment. Empirical studies show that the value of the standard deviation of shadowing path loss is ranged from 4 to 14 dB in outdoor channel, depending on the environment type.

The third model we use as a basis of comparison is a propagation model tailored to the transceivers used in the proposed system. In our case, that means tailoring the model to the devices we used for our measurements. The detailed specifications of the transceivers we used will be presented in Section 3. The formula tailored to the transceiver operation is [19]

$$P_{\mathrm{r}} = KP_{\mathrm{t}}/d^{\alpha} \tag{6}$$

where P_{t} is the transmit power and P_{r} is the received power measured at the receive antenna. Here, d is the distance between transmitter and receiver and α is the path loss exponent. The coefficient K is a constant function of transmit and receive antenna gains, and carrier frequency

$$K = G_{\mathrm{r}}G_{\mathrm{t}}\left(\frac{\lambda}{4}\right)^2. \tag{7}$$

By taking the logarithm on both sides of (7), we have the path loss equation in logarithmic units

$$\log(P_{\mathrm{r}}) = -\alpha\log(d) + \log(K) + \log(P_{\mathrm{t}}). \tag{8}$$

According to the experiments done by our group, the value of K for our transceivers is -5.9 dB. Accordingly, the path loss can be expressed as

$$L_{\mathrm{Mote}} = 5.9 + \alpha\log(d). \tag{9}$$

3 Field measurements

We measured receive signal strength using a Libelium–Waspmote transceiver shown in Fig. 2. It consists of a robust waterproof enclosure with external weatherproof and waterproof connectors for the sensors, a solar panel, antennas, and a universal serial bus cable to reprogramme the node. The Waspmote is an open source wireless sensor platform specifically focused on the implementation of low-power modes that extend the battery life of the nodes. The lifetime of the nodes varies depending on the duty cycle and the radio used.

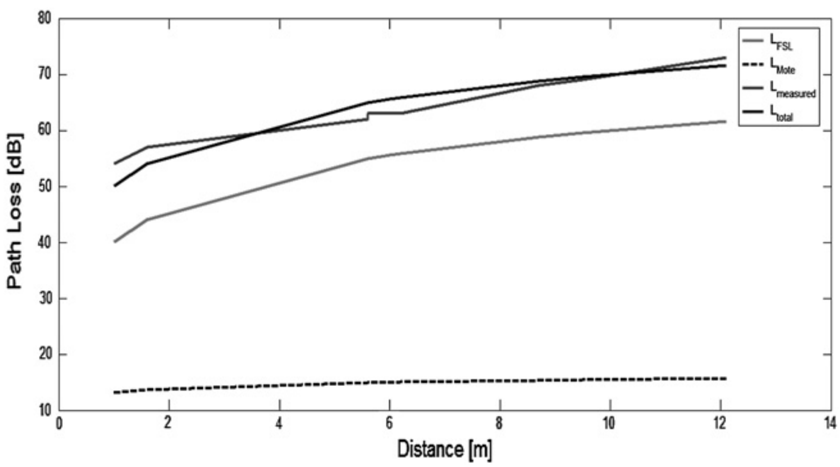

Fig. 5 *Path loss measured at UJB#1 on the first rig*

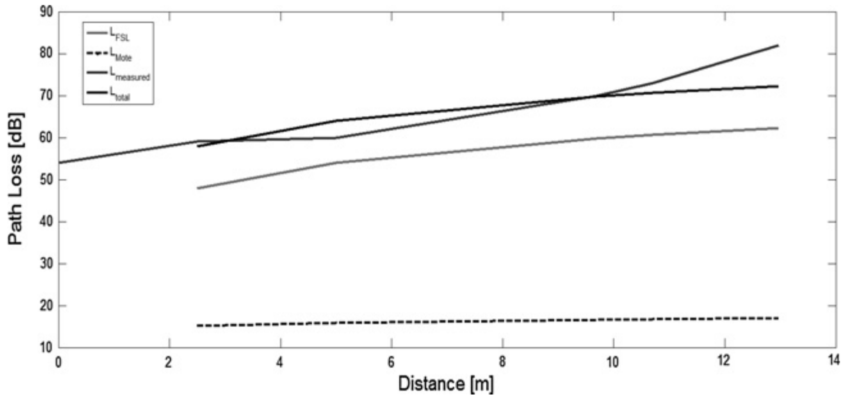

Fig. 6 *Path loss measured at UJB#2 on the first rig*

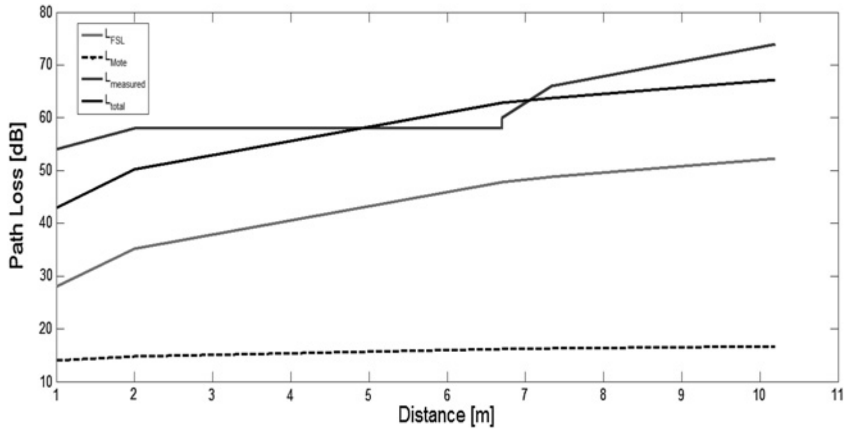

Fig. 7 *Path loss measured at UJB#1 on the second rig*

The Waspmote is based on a modular architecture. The idea is to integrate only the modules needed in each device, thus optimising costs. For this reason, all the modules (radios, sensor boards etc.) plug in via sockets. This device has the capability of operating with different standard protocols such as ZigBee, Wi-Fi, Bluetooth etc. We have completed our measurements using an 802.15.4 radio operating at a frequency of 2.4 GHz and a transmit power of 63 mW.

To measure the signal strength and derive the path loss model tailored to the actual wireless environment, we performed the measurement procedure on two different drilling rigs manufactured in Nisku, Alberta shown in Figs. 3 and 4. Each rig has two universal junction boxes (UJBs). These are the main hubs where the data transmitted by the various sensors on the rig is collected. These data could be pressure, temperature, gas density etc. Current practice is for the sensors to communicate with the UJBs via a wired network. This is costly to maintain, particularly as a result of rig moves. Our goal is to abolish existing wired networks, and establish a design procedure for reliable wireless communication network tailored to the rig environment. To achieve that goal, a reliable wireless channel model is required. Owing to the complexity of the rig environment, collecting field measurements, and exploiting regression models is a very good approach to

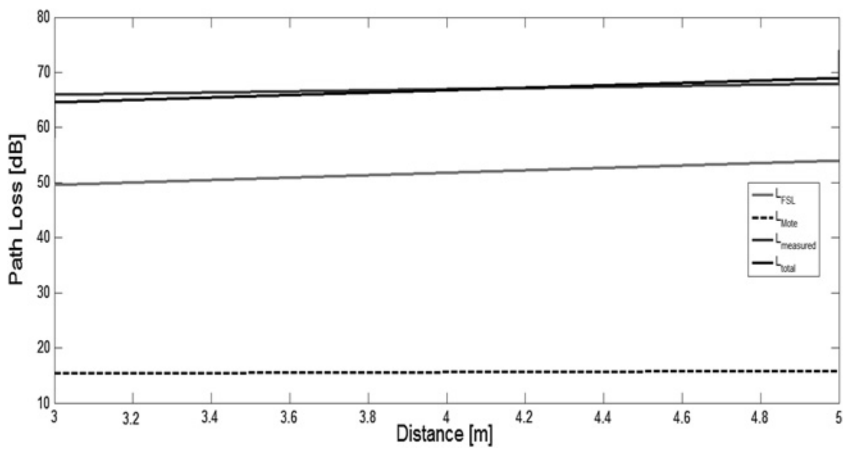

Fig. 8 *Path loss measured at UJB#2 on the second rig*

Table 1 Simulation parameters

simulators	OMNeT++ 4.3 and Castalia 3.2
simulation time	300 s
packets generated by each node	1500 (5 packets/s)
MAC protocol	802.15.4
transmission frequency	2.4 GHz
data rate	250 kbps
wireless channel	model derived in Sections 2 and 3

Table 2 SN parameters

Node	Location	Description	Data rate, packets/s
1	0, 0, 0	pressure sensor	5
2	0, 0, 30	depth sensor	5
3	0, 0, 15	electric torque sensor	5
4	0, 0, 0	hook-load sensor	5
5	0, 20, 0	flow paddle sensor	5
6	0, 50, 0	aggregator collecting data from different mud tank sensors through wired connection. It aggregates data of same time instance from all mud tank sensors and transmits as a single data packet	5
7	5, 50, 0	proximity sensor	5
8	0, 30, 0	additional node to support DMHR	0
9	5, 30, 0	additional node to support DMHR	0
Sink	0, 0, 0	Sink node receives data from all other nodes	–

establish an empirical model. Therefore, we measured the receive signal strength at the sensor locations, and analysed it to develop a propagation model well-suited to drilling rigs.

The measurement procedure has been executed as follows. As aforementioned, the data are collected at the UJB, and there are several sensors transmitting data. Therefore, in the wireless network, there will be an access point (AP) at the UJB. Accordingly, we located one transceiver at the UJB and connected it to the laptop to record the received signal strength. We moved a second transceiver to the locations of the different SNs distributed around the rig.

After moving to a new sensor location, and before recording any signal strength data, we would wait for 1 min to allow the signal to settle. In addition to the signal strength, we also measured the distance between each SN and the AP.

To describe the propagation environment, we define a parameter called the path loss exponent. This parameter defines how quickly signal strength attenuates as it travels through the propagation environment. We have estimated the values of this parameter for the environment in which we gathered the measurements. In the following, the measurement results will be presented and analysed.

4 Analysis and results

4.1 Wireless channel model

To derive the path loss model tailored to the actual drilling rigs, the received signal strength data were profiled and analysed with the aid of tools provided by the vendor. In addition, MATLAB has been utilised to obtain a better graphical perspective.

Fig. 5 shows the behaviour of the three previously detailed path loss models based on measurements from the first rig, given the locations of the UJB and sensors. The curves denoted L_{FSL}, L_{total}, and L_{Mote} are calculated from (3), (4) and (9), respectively. It also shows the actual path loss, L_{measured}, which is the difference between the transmit power and received power

$$L_{\text{measured}} = P_{\text{t}} - P_{\text{r}} \tag{10}$$

where P_{t} is 63 mW or 18 dBm. The measured path loss has almost the same trend as the total path loss, L_{total}, in which the path loss is less than the maximum allowable value for at least 98% of the locations.

The shadowing in the environment around UJB#1 has been modelled as a Gaussian random variable with standard deviation of 5 dB as there was at least one LOS path between the UJB and sensors. However, at the location of UJB#2, the standard deviation has been set to be 10 dB, as metallic obstacles blocked the paths to most of the sensors. The value of standard deviation in both cases has been selected based on the measurement results and by using the MATLAB curve fitting toolbox. Intuitively, propagation in the non-line-of-sight (NLOS) situation must suffer more from shadowing than in the LOS situation, thus explaining the higher standard deviation qualitatively.

Fig. 6 shows the situation at UJB#2. The observed trend in the measured values stems from the fact that though the sensors were located at a greater distance, there was an LOS path for communication, which implies lower path loss than the previous case.

The path loss analyses for UJB#1 and UJB#2 of the second rig are presented in Figs. 7 and 8, respectively. In Fig. 7, the standard deviation of the slow fading component is set to be 5 dB, whereas for UJB#2 it is set to be 7 dB. These values for standard deviation are similar to those for the first rig, and have also been obtained from curve fitting. The correspondence between L_{measured} and L_{total} in both figures shows that a slow fading propagation model can capture the path loss behaviour.

By comparing the measured signal strength with the path loss shadowing model, we conclude that a path loss exponent of 2.5–2.7 is sufficient to model the rig environment because a choice in this range results in L_{total} matching L_{measured} quite closely.

4.2 Performance of WSNs in a rig environment

Using simulation, we assess the performance of a WSN established on a rig. The simulation parameters are defined

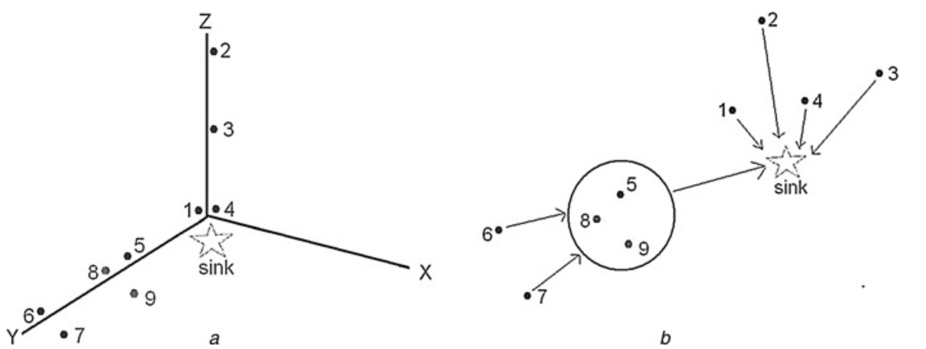

Fig. 9 *SN locations*

a Real rig environment
b Wireless links in DMHR

Each node maintains its own *RoutingTable*

- One entry for each *neighbour* towards the *Sink*
- Also has *link quality* and *energy* information of each *neighbour*

Periodic *CONTRL_PACKET* is broadcast by each node

- Contains *link quality* and *energy* information of the sending node
- Receiving node updates these data in corresponding *Routing Table* entry

Procedure Send (DATA)

select a list L of nodes from the Routing Table that have at least 20% of initial energy storage

If L ≠ Empty then

select node N1 from list L that has the best link quality

transmit DATA to node N1

Else

select node N2 from Routing Table that has the highest remaining energy

transmit DATA to node N2

End if

End Procedure

Fig. 10 *DMHR algorithm*

in Table 1, out of which propagation loss predictions are characterised based on the wireless channel model derived in the previous section. Fig. 9*a* shows SN placements on a real drilling rig.

Table 2 describes the details of the SNs. Sensor coordinates are given in metres. The data rate of each sensor is the rate at which it generates measurements. Dynamic multi-hop routing protocol (DMHR) is the dynamic multi-hop routing protocol, which will be described next.

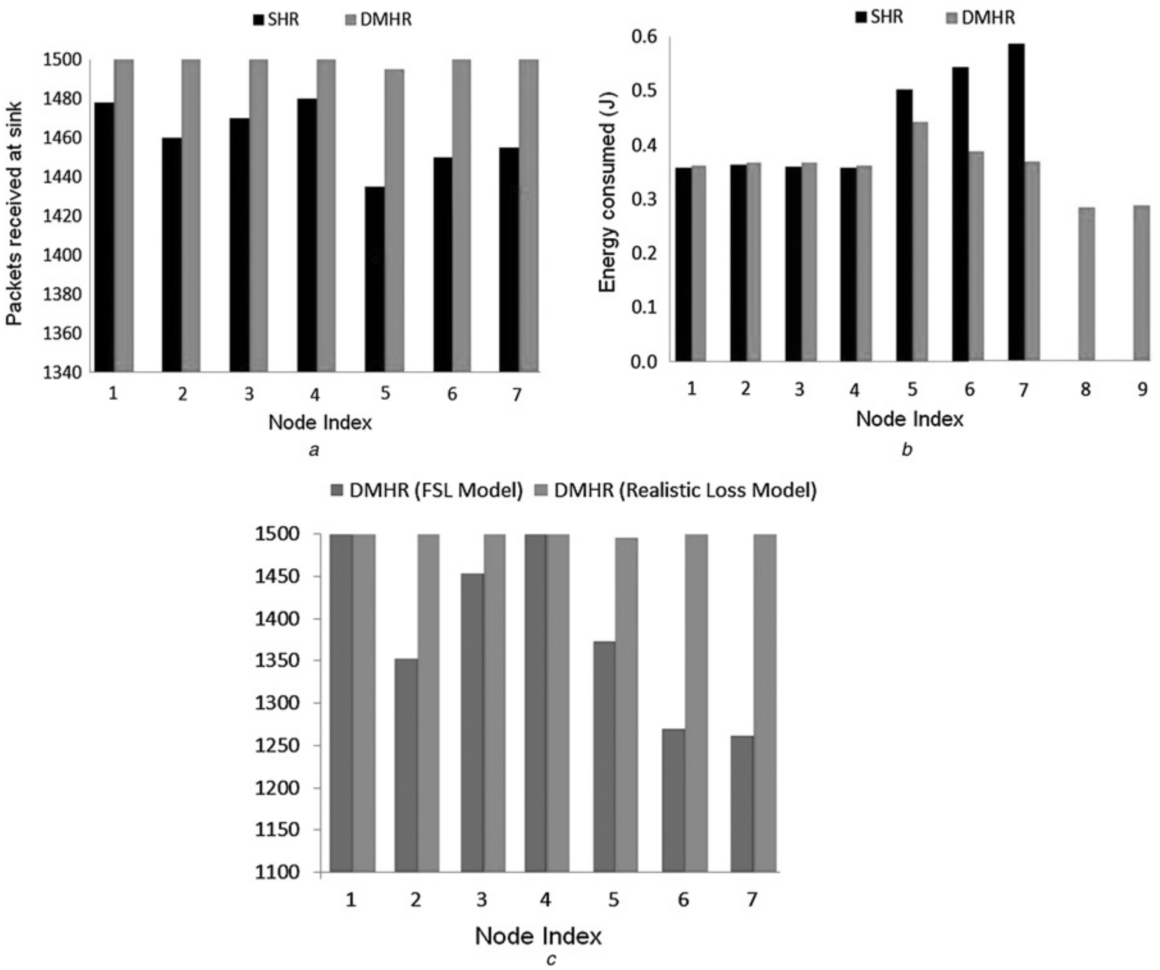

Fig. 11 *Performance of WSN*

a Packets successfully received at the Sink
b Energy consumed by each node
c Success rates of nodes under DMHR considering FSL and realistic loss in transmission power estimation

Single-hop forwarding constrains the physical coverage and decreases the packet success rate of a WSN because packets must travel direct from each SN to the UJB. We designed a novel multi-hop routing protocol to improve the performance of the WSN by removing the limits of single-hop forwarding. In our test case, sensors 1–4 send data directly to the UJB, which is also called the Sink (Fig. 9*b*). Nodes 5, 8, and 9 act such as a cluster to forward data transmitted by nodes 6 and 7. Nodes 6 and 7 select the node used to relay their data. That is, nodes 6 and 7 send each data packet to exactly one node inside the cluster. DMHR dynamically selects a node from the cluster based on link quality, and the energy reserves of the nodes inside the cluster. The algorithm is described in Fig. 10.

Nodes 8 and 9 do not generate any data of their own – they simply forward data received from other nodes. The efficacy of DMHR has been compared with a traditional single-hop routing (SHR) protocol. In SHR, every node sends data directly to the Sink (dummy nodes 8 and 9 are not required in this protocol). Fig. 11*a* compares DMHR with SHR in terms of the number of packets received from each node at the Sink and Fig. 11*b* compares the energy consumed by individual nodes in the network. Fig. 11*a* shows that the packet success rates of all nodes are almost 100% in DMHR, whereas the rates are much lower in SHR. As DMHR can change routes based on link quality, it avoids unreliable links and consequently achieves a high packet success rate. In SHR, every node sends data directly to the Sink. To do that, nodes far away from the Sink (such as nodes 6 and 7) must use high transmission power. This high transmission power (as well as fixed routes) causes high interference with other nodes. As a result, packet success rates of all nodes are affected adversely in SHR.

Network lifetime is determined by the maximum rate at which energy is consumed by any node during network operation. Fig. 11*b* shows that the energy consumed by individual nodes is nearly uniform in DMHR, whereas with SHR nodes 6 and 7 consumed energy at a much higher rate than the other nodes.

In SHR, nodes 6 and 7 use high transmission power to send data directly to the Sink. As a result, these two nodes consume a large amount of energy during network operation. In DMHR, all packets generated by nodes 6 and 7 are forwarded to the Sink through nodes 5, 8, and 9. Though this introduces additional cost of deploying nodes 8 and 9, this distributes energy consumption of node 5 over nodes 8 and 9. Consequently, all nodes consume nearly the same amount of energy. As a result, no individual node in DMHR runs out of energy more quickly than the others. Consequently, the network would have the longest possible lifetime.

Fig. 11*c* shows the necessity of accurate channel modelling of the wireless channel in a drilling rig environment. In this figure, we have examined the performance of the WSN under the realistic channel model measured in the location of the drilling rig. As it can be observed, the WSN has a better performance under the realistic channel model than the FSL channel model which is a simple path loss model. Two different cases have been compared for the WSN of Fig. 9*a*, with DMHR. In case 1, the transmission power of each node has been determined based only on FSL. In case 2, the transmission power of each node has been determined based on our channel model. In case 2, we basically tried to assess the combined effect of wireless channel parameters found in the field study and the proposed DMHR on the performance of network operations. Naturally, transmission power is lower in case 1 because only FSL is accounted for. Fig. 11*c* shows that the packet success rates of individual nodes in case 1 are up to 16% less (depending on node location) as compared with case 2. In case 2, the required transmission power of each node has been determined based on our field measurements in real rig environments. The results are as expected, and demonstrate that our model is a reliable network design tool. When only FSL is considered during determination of node transmission power, losses due to obstructions and other environmental factors are ignored. Consequently, lower levels of transmission power are determined, and the nodes will experience transmission failures when deployed in the actual environment. With accurate modelling, the correct transmit power levels can be predetermined.

5 Conclusion

In this paper, investigation of the wireless propagation channel model on a drilling rig has been conducted. Our measurement results show that a shadowing path loss model is sufficient to model the wireless channel established between sensors. A path loss exponent in the range of 2.5–2.7 characterises this path loss model. We also utilised the proposed propagation model for assessment of WSN performance on a drilling rig. We developed a dynamic multi-hop routing protocol, and found that it yields a significant improvement in WSN performance in terms of packet success rate, and decreased energy consumption.

6 References

1 Tse, D., Viswanah, P.: ‘Fundamentals of wireless communications’ (Cambridge University Press, New York, NY, 2005)
2 Zhang, J., Li, W., Han, N., *et al.*: ‘Forest fire detection system based on a ZigBee wireless sensor network’, *Front. Forestry China*, 2008, **3**, (3), pp. 369–374
3 Simoni, S., Padoan, S., Nadeau, D.F., *et al.*: ‘Hydrologic response of an alpine watershed: application of a meteorological wireless sensor network to understand streamflow generation’, *Water Resour. Res.*, 2011, **47**, (10), pp. 1–16
4 Song, W.Z., Huang, R., Xu, M., *et al.*: ‘Design and deployment of sensor network for real-time high-fidelity volcano monitoring’, *IEEE Trans. Parallel Distrib. Syst.*, 2010, **21**, (11), pp. 1658–1674
5 Tovar, A., Friesen, T., Ferens, K., *et al.*: ‘A DTN wireless sensor network for wildlife habitat monitoring’. Proc. 23rd Canadian Conf. on Electrical and Computer Engineering (CCECE), 2010, pp. 1–5
6 Han, X., Cao, X., Lloyd, E., *et al.*: ‘Fault-tolerant relay node placement in heterogeneous wireless sensor networks’, *IEEE Trans. Mob. Comput.*, 2010, **9**, (5), pp. 643–656
7 Yedavalli, K., Krishnamachari, B., Venkatraman, L.: ‘Fast/fair mobile localization in infrastructure wireless sensor networks’, *SIGMOBILE Mob. Comput. Commun. Rev.*, 2007, **11**, (1), pp. 29–40
8 Oyman, E., Ersoy, C.: ‘Multiple sink network design problem in large scale wireless sensor networks’. 2004 IEEE Int. Conf. on Communications, 2004, vol. 6, pp. 3663–3667
9 Bhuiyan, M.M., Gondal, I., Kamruzzaman, J.: ‘I-MAC: energy efficient intelligent MAC protocol for wireless sensor networks’. Proc. of Asia Pacific Conf. on Communication (APCC 2011), October 2011, pp. 1–6
10 Zhang, H., Shen, H.: ‘Balancing energy consumption to maximize network lifetime in data-gathering sensor networks’, *IEEE Trans. Parallel Distrib. Syst.*, 2009, **20**, (10), pp. 1526–1539
11 Akkas, M.A., Akyildiz, I.F., Sokullu, R.: ‘Terahertz channel modeling of underground sensor networks in oil reservoirs’. Proc. IEEE GLOBECOM, 2012, pp. 543–548
12 Akyildiz, I.F., Stuntebeck, E.P.: ‘Wireless underground sensor networks: research challenges’, *Ad Hoc Netw.*, 2006, **4**, pp. 669–686
13 Shao, Q., Zhang, Z., Zhang, Z.: ‘Research on safety monitoring system of mine based on *ad hoc* technology’. Proc. of the Int. Conf. on Information Management, Innovation Management and Industrial Engineering, November 2013, pp. 450–453
14 Yang, Y., Zhang, S., Wang, Q., *et al.*: ‘Long distance wireless sensor networks applied in coal mine’, *Procedia Earth Planet. Sci.*, 2011, **1**, pp. 1461–1467
15 Xiao, S., Wei, X., Wang, Y.: ‘A multipath routing protocol for wireless sensor network for mine security monitoring’, *Min. Sci. Technol.*, 2010, **20**, pp. 148–151
16 Guo, Y., Wang, Q., Huang, H., *et al.*: ‘The research and design of routing protocols of wireless sensor network in coal mine data acquisition’. Proc. of the Int. Conf. on Information Acquisition, July 2007, pp. 25–28
17 Niu, X., Xi, H., Zhao, Z., *et al.*: ‘The design and evaluation of a wireless sensor network for mine safety monitoring’. Proc. of the IEEE Global Telecommunications Conf., December 2012, pp. 1291–1295
18 Aslam, M.I., Zekavat, S.A.: ‘New channel path loss model for near-ground antenna sensor networks’, *IET J. Wirel. Sens. Syst.*, 2012, **2**, (2), pp. 103–107
19 Chen, Y.: ‘Chernoff information path loss in wireless relay sensor networks’, *IET J. Wirel. Sens. Syst.*, 2012, **2**, (3), pp. 201–213
20 Friis, H.T.: ‘A note on a simple transmission formula’, *Proc. IRE*, 1946, **34**, pp. 254–256
21 Molisch, A.: ‘Wireless communications’ (Wiley-IEEE Press, United Kingdom, 2011)