2011

Topology Analysis of Wireless Sensor Networks for Sandstorm Monitoring

P. Wang
Georgia Institute of Technology

Z. Sun
Georgia Institute of Technology

Mehmet C. Vuran
University of Nebraska-Lincoln, mcvuran@cse.unl.edu

M. A. Al-Rodhaan
King Saud University

A. M. Al-Dhelaan
King Saud University

See next page for additional authors

Wang, P.; Sun, Z.; Vuran, Mehmet C.; Al-Rodhaan, M. A.; Al-Dhelaan, A. M.; and Akyildiz, I. F., "Topology Analysis of Wireless Sensor Networks for Sandstorm Monitoring" (2011). *CSE Conference and Workshop Papers*. 284.
http://digitalcommons.unl.edu/cseconfwork/284

Authors
P. Wang, Z. Sun, Mehmet C. Vuran, M. A. Al-Rodhaan, A. M. Al-Dhelaan, and I. F. Akyildiz

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE ICC 2011 proceedings

Topology Analysis of Wireless Sensor Networks for Sandstorm Monitoring

P. Wang*, Z. Sun*, M. C. Vuran†, M. A. Al-Rodhaan‡, A. M. Al-Dhelaan‡, and I. F. Akyildiz*‡

*Broadband Wireless Networking Laboratory, School of Electrical and Computer Engineering
Georgia Institute of Technology, Atlanta, GA, 30332, USA
Email: {pwang40; zsun; ian}@ece.gatech.edu
†Cyber-Physical Networking Laboratory, Department of Computer Science and Engineering
University of Nebraska-Lincoln, Lincoln, NE 68588 USA
E-mail: mcvuran@cse.unl.edu
‡College of Computer and Information Sciences, King Saud University, Riyadh, Saudi Arabia
E-mail: {rodhaan, dhelaan}@ksu.edu.sa

***Abstract*—Sandstorms are serious natural disasters, which are commonly seen in the Middle East, Northern Africa, and Northern China.In these regions, sandstorms have caused massive damages to the natural environment, national economy, and human health. To avoid such damages, it is necessary to effectively monitor the origin and development of sandstorms. To this end, wireless sensor networks (WSNs) can be deployed in the regions where sandstorms generally originate so that sensor nodes can collaboratively perform sandstorm monitoring and rapidly convey the observations to remote administration center. Despite the potential advantages, the deployment of WSNs in the vicinity of sandstorms faces many unique challenges, such as the temporally buried sensors and increased path loss during sandstorms. Consequently, the WSNs may experience frequent disconnections during the sandstorms. This further leads to dynamically changing topology. In this paper, a topology analysis of the WSNs for sandstorm monitoring is performed. Four types of channels a sensor can utilize during sandstorms are analyzed, which include air-to-air channel, air-to-sand channel, sand-to-air channel, and sand-to-sand channel. Based on the channel model solutions, a percolation-based connectivity analysis is performed. It is shown that if the sensors are buried in low depth, allowing sensor to use multiple types of channels improves network connectivity. Accordingly, much smaller sensor density is required compared to the case, where only terrestrial air channels are used. Through this topology analysis a WSN architecture can be deployed for very efficient sandstorm monitoring.**

I. INTRODUCTION

Sandstorms cause massive damages to the natural environment, national economy, and human health in the Middle East, Northern Africa, and Northern China. Among these damages, sandstorms play an important role in the spread of diseases by blowing virus spores on the ground into the atmosphere. In addition, the significantly reduced visibility interrupts aircraft and road transportation. Sandstorms also cause forced dust injection, which greatly damages human respiratory system. These serious consequences necessitate effective sandstorm forecasting systems to provide timely and accurate sandstorm warnings.

Nowadays, several sandstorm forecasting systems have been deployed to serve different regions and countries. These systems include the Mediterranean Dust Regional Atmospheric Model (DREAM) system [10], the Asian Dust Aerosol Model (ADAM) system [11], and the Chinese Unified Atmospheric Chemistry Environment for Dust (CUACE) system [6]. These existing systems, however, face challenges in providing accurate sandstorm forecasting because they lack real-time observation capabilities from the sandstorm sources, such as relative humidity, maximum surface winds, and maximum temperature. Specifically, the current forecasting systems, such as CUACE [6], heavily rely on meteorological stations to collect and transmit the meteorological and geographic information. However, meteorological stations have to be deployed in the potential sand source regions to provide real-time environment monitoring. Such a strategy is not feasible in certain areas such as Middle East, where the deserts are the main origins of sandstorms. In addition, due to their high deployment cost, the density of existing meteorological stations is not sufficient to yield an acceptable coverage for accurately locating the regions where sandstorms originate.

To address these challenges, in-situ coverage of sandstorms is required using low-cost monitoring devices. To this end, wireless sensor networks provide a promising solution to realize real-time environment monitoring, large-area coverage, on-site data processing, and rapid information delivery. Specifically, WSNs can be easily deployed by dropping the ground sensors from a plane so that sensors are quickly and efficiently placed in a large target area. To prevent the deployed sensors flying away during sandstorms, each sensor is tied to an anchor. After a wireless sensor network is deployed, the networked sensors can collaboratively collect real-time meteorological and dust information such as atmospheric pressure, temperature, humidity, wind speed, and soil moisture status. The gathered information is then preprocessed, aggregated/compressed, and transmitted to a remote control center, where sophisticated forecasting models can utilize this information to initiate corresponding sandstorm warnings.

Despite the promising aspects of WSNs in sandstorms, there are still many open research issues remaining to be resolved for practical implementation. One of the major issues is how to maintain network connectivity under the impact of sandstorms.

2011 IEEE International Conference on Communications (ICC)
Pages 1 - 5. DOI: 10.1109/icc.2011.5963393

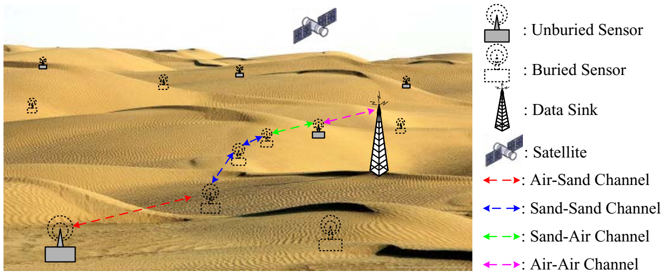

Fig. 1. Network Architecture

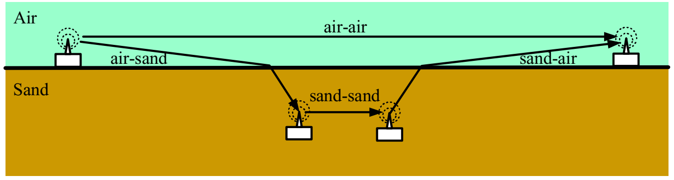

Fig. 2. Four Types of Channels

More specifically, it has been reported that during sandstorms, terrestrial air channels can exhibit an additional path loss of 10 dB to 26 dB [5]. In addition, due to wind dynamics, the sensor nodes can be temporally buried in the sands or exposed above the ground. The first fact implies the reduced transmission range because of the decreased SNR at receivers, while the second implies the reduced node density since a large portion of sensor nodes may be buried in the sands. The above two facts indicate that the WSN may experience frequent disconnections during the sandstorms even through good connectivity is guaranteed when the network is initially deployed. To encounter this problem, we allow sensors to use four types of channels based on the locations of the transmitters and receivers, including air-to-air (AA) channel, air-to-sand (AS) channel, sand-to-air (SA) channel, and sand-to-sand (SS) channel [13]. By such channel diversity/variability, sensor nodes can connect to the remote sink through multi-hop paths as long as at each hop along a path there exists at least one type channel available.

Although such communication scheme has potential advantages, the connectivity analysis of such scheme is complicated due to the coexistence of multiple types of channels. To solve this problem, we investigate the connectivity issue from the percolation perspective [9]. Percolation theory concerns a phase transition phenomenon where the network exhibits fundamentally different behavior when the node density λ is below or above the critical density λ_c. If $\lambda > \lambda_c$, the network contains an extremely large connected component such that each node in this component can communicate with each other. In this case, the network is considered to be connected. If $\lambda < \lambda_c$, the network is partitioned into small fragments, and thus becomes unconnected and unusable. Percolation theory has been proven to be a very useful tool for the analysis of large-scale wireless networks [4], [8].

In this paper, we first provide the analytical results of the path loss of the four types of channels. Based on the path loss analysis, the transmission range of each channel is derived, which completely depends on the environmental conditions. Then, we prove that there also exists a critical density λ_c^{Cross} for the WSNs under the impact of sandstorms. It is shown that λ_c^{Cross} is a function of the wind dynamics of sandstorms and the transmission ranges of multiple types of channels. Accordingly, we demonstrate that when sensors are buried in shallow depth, λ_c^{Cross} is smaller than λ_c^{AA}, the critical density of the single medium communication scheme, which only uses terrestrial air channels. This implies that jointly using multiple types of channels improves network connectivity. Accordingly, smaller node density is required for achieving the same connectivity performance as the single medium case, i.e., only air-to-air communication.

The rest of this paper is organized as follows. Section II introduces the network architecture and channel models. In Section III, we present the topology analysis based on percolation theory. Finally, Section IV concludes this paper.

II. NETWORK ARCHITECTURE AND CHANNEL MODELS

To acquire the real time and comprehensive measurements of the sand source, in a WSN, a great number of unattended ground sensors are deployed in the vast desert area, as shown in Fig. 1. The humidity, temperature, soil moisture, and wind speed/direction of the desert are measured by those sensors. The measurements of each sensor are then transmitted in a multi-hop fashion to a data sink. The data sink collects the sensing reports from the sensors and detects possible sandstorms by fusing the sensing reports. Then, the data sink forwards the detection reports to the remote administration center through satellite links.

Based on the network architecture, we find that the network connectivity is essential to maintain the system functionality. However, due to the harsh environmental conditions of the desert, the sensors can be temporarily buried by sands frequently due to the wind dynamics. Consequently, the wireless communication between sensors can be severely affected and the network connectivity is degraded.

To mitigate the impacts of sandstorms on network connectivity, we employ the use of multiple types of channels in sandstorm monitoring. Specifically, under such communication paradigm, the sensor nodes that are temporarily buried in the sands still maintain their communication abilities but with smaller transmission ranges. Based on the locations of the transmitters and receivers, four types of channels are utilized, including air-to-air (AA) channel, air-to-sand (AS) channel, sand-to-air (SA) channel, and sand-to-sand (SS) channel, as shown in Fig. 2 [13]. Then, two sensor nodes (either buried in sand or unburied) can be connected through multi-hop relays, where the relay sensor nodes can also be either buried in sand or unburied. As a result, the impact of the sandstorms on the network connectivity can be effectively mitigated.

Despite the potential advantages, the connectivity analysis in networks with four types of channels is complicated. The transmission range of the four types of channels are different and are highly dynamic as the changes of environmental conditions. In the rest of this subsection, we provide the analytical results of the path loss of the four types of channels as functions of the environmental conditions. Then, the transmission ranges can be derived based on the path loss. Since the wireless communications in sands can be viewed as a special case of the underground communications [1], the following channel analysis is based on our previous analysis on the wireless underground channel characteristics [2], [14].

A. Air-to-air channel

It has been reported that the sandstorm can cause an additional path loss of 10 dB to 26 dB that for duration of several minutes [5]. Therefore, the path loss of the air-to-air channel L_{AA} can be calculated using the Friss equation:

$$L_{AA}(d_{_{air}}) = -147.6 + 20\log d_{_{air}} + 20\log f + L_{_{sandstorm}} \ . \tag{1}$$

where $d_{_{air}}$ is the length of the air path; f is the operating frequency; $L_{_{sandstorm}}$ is the additional path loss caused by the sandstorm that is in the range of 10 dB to 26 dB.

B. Sand-to-sand channel

The path loss of Sand-to-sand channel consists of two parts: the sand path loss $L_{_{sand}}$ and the additional path loss $V_{_{reflect}}$ caused by the reflected second path from the air-ground interface, as shown in Fig. 2.

$$L_{SS}(d_{_{sand}}) = L_{_{sand}}(d_{_{sand}}) + V_{_{reflect}}(h_u) \ , \tag{2}$$

where the UG path loss $L_{_{sand}}$ is a function of sand path length $d_{_{sand}}$, operating frequency, water content, and sand bulk density; the additional path loss $V_{_{reflect}}$ is a function of all the parameters of $d_{_{sand}}$ plus the burial depth h_u of UG sensors. The expressions of $L_{_{sand}}(d_{_{sand}})$ and $V_{_{reflect}}(h_u)$ can be found in [2], [14].

C. Sand-to-air channel and air-to-sand channel

The path loss of the sand-to-air channel L_{SA} consists of three parts: the sand path loss L_{sand}, the air path loss L_{AA} and the refraction loss from sand to air $L^R_{_{S-A}}$:

$$L_{SA}(d_{_{sand}}, d_{_{air}}) = L_{_{sand}}(d_{_{sand}}) + L_{AA}(d_{_{air}}) + L^R_{_{S-A}} \ , \tag{3}$$

where $d_{_{sand}}$ is the length of the sand path, and the $d_{_{air}}$ is the length of the air path, as shown in Fig. 2. Similar to the sand-to-air channel, the path loss of the air-to-sand channel is:

$$L_{AS}(d_{_{sand}}, d_{_{air}}) = L_{_{sand}}(d_{_{sand}}) + L_{AA}(d_{_{air}}) + L^R_{_{A-S}} \ , \tag{4}$$

where $L^R_{_{A-S}}$ is the refraction loss from air to sand. In (3) and (4), the sand path loss $L_{_{sand}}$ and air path loss L_{AA} can be derived from (2) and (1), respectively; the detailed expression of the refraction loss $L^R_{_{S-A}}$ and $L^R_{_{A-S}}$ can be found in [2], [14], which are functions of the sand dielectric properties, the burial depth of sensor, the distance between the transceivers, and the antenna height of the sensors.

D. Transmission Ranges of the Four Types of Channels

Assuming that the transmit power of the sensor is P_t, the antenna gains of the receiver and transmitter are g_r and g_t. Then the received power, $P_r(d)$, at a receiver sensor node d meters away is $P_r(d) = P_t + g_r + g_t - L_{_{path}}(d)$, where $L_{_{path}}(d)$ is the corresponding path loss calculated either by (1), (2), (3), or (4). Then the corresponding transmission range of the channel is:

$$R = \max\{d : P_r(d)/P_n > SNR_{th}\} \ , \tag{5}$$

where P_n is the noise power; and SNR_{th} is the minimum signal-to-noise ratio required by the receiver.

In the following, we use R_{aa}, R_{ss}, R_{sa}, and R_{as} to denote the transmission ranges of air-to-air channel, sand-to-sand channel, sand-to-air channel, and air-to-sand channel, respectively. According to the above analysis, due to the high path loss in the sand medium, R_{ss} is very limited (no more than 10 meters). R_{aa} is the largest (more than 100 meters) since the path loss in the air is the smallest. R_{sa} and R_{as} are in the range of 30 meters to 70 meters, depending on the burial depth and sand property. It should be noted that R_{sa} is larger than R_{as}, since a large portion of signal energy can penetrate the air-to-sand interface from sand to air while most energy is reflected back in the opposite direction. However, this difference becomes smaller when the sensor burial depth decreases [13].

III. TOPOLOGY ANALYSIS

A. Random Geometric Graph

To perform the percolation-based topology analysis, We use random geometric graph to model a WSN. In particular, the sensor nodes are distributed according to homogeneous Poisson point process with density λ. Let $X^n_{i=0}$ denote the locations of sink $\{0\}$ and the nodes $\{1, 2, ..., n\}$. A communication link exists between two nodes $\{i, j\}$ if their mutual distance, $||X_i - X_j||$, is less than the transmission range R so that the SNR at the receiver is sufficiently large for successfully decoding. The graph with all node pairs $\{i, j\}$ with $||X_i - X_j|| < R$ is called a random geographic graph, denoted by $G(\lambda, r)$.

By continuum percolation theory [9], there exists a critical density $0<\lambda_c<\infty$ such that if $\lambda > \lambda_c$, there exists an infinite connected component, i.e., a connected component with an infinite number of nodes, in $G(\lambda, R)$. The exact value for λ_c is not known. For the random disk graph with r = 1, i.e., $G(\lambda, 1)$, numerical simulations show that $1.43<\lambda^1_c<1.44$ [12].

B. Effective Transmission Range of Jointly Using Multiple Types of Channels

Different from the conventional terrestrial sensor networks, the ground sensors of a WSN can be temporally buried in the sands caused by the wind dynamics. To model this phenomena, each sensor node is associated with an independent and identically distributed (i.i.d.) alternating renewal process, denoted by $S(t)$, which alternates between two states: the ON state, during which the sensor is exposed on the ground; and the OFF state, during which the sensor is buried in sand. Denote the length of ON and OFF state by $\tau_0 > 0$ and $\tau_1 > 0$ respectively. Assume τ_0 (τ_1) follows an arbitrary distribution with finite expectation, i.e., $E(\tau_0) < \infty$ and $E(\tau_1) < \infty$. Based on the above assumptions, the marginal distribution of $S(t)$ is given by

$$\begin{aligned} P_{ex} &= Pr(S(t)=0) = \frac{E(\tau_0)}{E(\tau_0)+E(\tau_1)} \\ P_{bu} &= Pr(S(t)=1) = \frac{E(\tau_1)}{E(\tau_0)+E(\tau_1)} \end{aligned} \quad (6)$$

where P_{ex} and P_{bu} denotes the probability that at an arbitrary time instance a sensor node stays exposed and buried, respectively. According to the thinning theory of Poisson point process [9], the exposed and buried sensors are still distributed as Poisson point processes with density of $P_{ex}\lambda$ and $P_{bu}\lambda$, respectively.

When sensors are allowed to use multiple types of channels, the buried sensors can act as the relay nodes for the unburied sensors. Therefore, as shown in Fig. 2, a communication link between two unburied sensors consists of three sublinks: air-to-sand (AS) sublink, sand-to-sand (SS) sublink, and sand-to-air (SA) sublink, with length denoted by L_{as}, L_{ss}, and L_{sa}, respectively. Therefore, the effective transmission range R_{eff} can be expressed by

$$R_{eff} = L_{as} + L_{ss} + L_{sa}. \quad (7)$$

The AS and SA sublink is only used for 1-hop connection, i.e., AS sublink connects the unburied source node to a buried relay node, while SA sublink connects a buried relay node to the unburied destination node. Therefore, we have

$$L_{as} = R_{as}, \quad L_{sa} = R_{sa} \quad (8)$$

In contrary, the SS sublink can be a multi-hop path between two buried nodes that connect the unburied source and destination nodes, respectively. Thus, the length of the SS sublink depend on several factors, including $P_{bu}\lambda$, R_{ss}, R_{sa}, and R_{as}. Intuitively, as $P_{bu}\lambda$ and R_{ss} increase, so does the probability that longer SS sublinks exist. In addition, as R_{sa} and R_{as} increase, so does the probability that such SS sublinks can connect two randomly selected unburied nodes.

To simplify our analysis of Lss, we consider the case where the sensors are buried in shallow depth. According to our channel analysis, this indicates that the sand-to-air and air-to-sand channels are symmetric, i.e.,

$$R_{sa} \approx R_{as} \quad (9)$$

In this case, applying scaling relation for continumm percolation [3], the SS sublink length is given by

$$L_{ss}(\lambda) = 2k\big(\frac{R_{ss}}{2R_{as}-R_{ss}}\phi(\pi\frac{R_{ss}^2}{4}P_{bu}\lambda)\big)^{\alpha}(R_{as}-\frac{R_{ss}}{2}) \quad (10)$$

and

$$\phi(x) = kx(1+cx)(1-\frac{4x}{\pi\lambda_c^1})^{-1/2} \quad (11)$$

where $\alpha = 3/8$, $k = 0.25$, and $c = 2.20$. Combining Equ. (7), (9), and (10) yields the effective transmission range R_{eff}, i.e.,

$$R_{eff} = 2R_{as} + L_{ss}(\lambda) \quad (12)$$

It is worth to note that although the above equation is derived in the case where sensors are buried in the shallow sands, this equation can serve as a conservative estimate of R_{eff} when the sensors are buried deeply since in this case we have $R_{as} < R_{sa}$, according to our channel analysis.

C. Critical Density

Based on the derived effective transmission range R_{eff}, we next study the critical density of WSNs. This density λ_c plays a key role in the network deployment phase. If the deployed node density $\lambda > \lambda_c$, then the WSN is connected from the percolation perspective, i.e., there exists an extremely large portion of sensors that can connect to the sink. Otherwise, if $\lambda < \lambda_c$, the WSN would be partitioned into small fragments, and thus becomes unconnected. Next, we derive the critical density λ_c under three cases: pure SS communications, pure AA communications, and communications with multiple types of channels. For pure AA communications, applying the scaling property of continuum percolation, we have the critical density λ_c^{SS}, i.e.,

$$\lambda_c^{SS} = \lambda_c^1 / R_{ss}^2 \quad (13)$$

Obviously, if $\lambda > \lambda_c^{SS}$, the network can keep connected without being affected by the wind dynamics, which are characterized by P_{bu} in Equ. (6). This is due to the fact that the condition $\lambda > \lambda_c^{SS}$ guarantees that even when all sensors are buried in sands, they can still reach the data sink by multi-hop paths made of short-range SS channels. Since R_{ss} is generally very short, this indicates that extremely high node density is required. Considering its high deployment cost, such scheme is not practical and thus we have $\lambda < \lambda_c^{SS}$.

If pure AA channels are utilized to establish connections, at an arbitrary time instance, such channels are only applicable for $(1-P_{bu})\lambda$ of sensors. Thus, applying thinning theory of Poisson point processes [9], the critical density λ_c^{AA} follows

$$\lambda_c^{AA} = \frac{\lambda_c^1}{R_{aa}^2(1-P_{bu})} \quad (14)$$

The above equation indicates that as the probability that a sensor is buried in the sands increases, the sensor nodes have to be deployed in higher density to maintain network connectivity.

We now consider communications with multiple types of channels, where a pair of nodes is mutually connected if they reside within the effective transmission range R_{eff} of each other. In this case, the critical density λ_c^{Cross} can be derived by solving following equation

$$(1-P_{bu})\lambda_c^{Cross} = \frac{\lambda_c^1}{\big(2R_{as} + L_{ss}(\lambda_c^{Cross})\big)^2} \quad (15)$$

According to Equ.(10), λ_c^{Cross} is a function in terms of R_{ss}, R_{as}, and P_{bu}, i.e.,

$$\lambda_c^{Cross} = f(R_{ss}, R_{as}, P_{bu}) \quad (16)$$

The analysis above investigates the connectivity issue at a given time instance. To incorporate the wind dynamic process $S(t)$, we apply the similar method as the one used in the proof of dynamic percolation [7] and have the following Theorem.

Theorem 1: Given a WSN $G(\lambda, R_{eff})$ and wind dynamics modeled by alternating renewal process $S(t)$ with $Pr(S(t)=1) = P_{bu}$, there exists a critical density $\lambda_c^{Cross} = f(R_{ss}, R_{as}, P_{bu})$ for the communication scheme allowing multiple types of channels, such that if $\lambda > \lambda_c^{Cross}$ then with

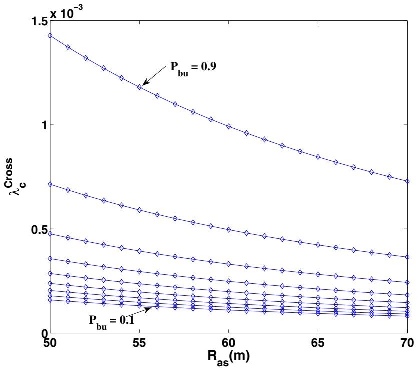

Fig. 3. Critical density based on communication scheme with multiple types of channels

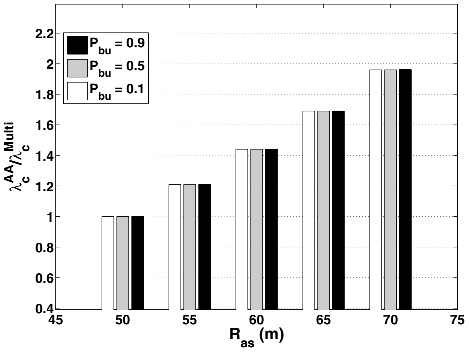

Fig. 4. Critical density ratio of single medium communication scheme and communication scheme with multiple types of channels

probability one, there exists an infinite connected component in the $G(\lambda, R_{eff})$ for all times $t > 0$.

Proof: Refer to [7] for details. ■

D. Performance Evaluation

We now evaluate the network topology by measuring the critical densities. Specifically, we measure λ_c^{Cross} and λ_c^{AA}, respectively, varying the wind dynamic parameter P_{bu} and the buried depth of sensors d. If the measured λ_c^{Cross} is less than λ_c^{AA}, this implies that jointly using multiple type of channels require smaller node density to achieve the same connectivity performance as the single medium communication scheme, which only uses terrestrial air channels. Other simulation parameters are set as follows: All the transceivers in sensors are the same. The transmitting power is 10 mW at 900 MHz. The minimum received power for correct demodulation is -90 dBm. The antenna gains $g_t = g_r = 5$ dB. The volumetric water content (VWC) in the sand is 1%.

In Fig. 3, λ_c^{Cross} is shown in the case, where the sensors are buried in shallow depth and the burial depth of the sensor's antenna is less than 0.1 m. In this case, by channel analysis in Section II, R_{as} approximately ranges from 50m to 70m, where smaller value is obtained at shallower depth. It can be seen that λ_c^{Cross} decreases as R_{as} increases. This is as expected since larger R_{as} indicates larger R_{eff} and thus smaller λ_c^{Cross}. In addition, we observe that higher P_{bu} leads to larger λ_c^{Cross}. This observation is due to the fact that higher P_{bu} implies more sensors are buried. Accordingly, more sensors have to be deployed to compensate the buried sensors.

In Fig. 4, the ratio of λ_c^{AA} to λ_c^{Cross}, i.e., $r = \lambda_c^{AA}/\lambda_c^{Cross}$, is shown. Specifically, it can be observed that as the R_{as} increases, the ratio r increases from 1 to 2.25. This implies that in the shallow sand case, single medium communication require more than 2 times the amount of sensors to ensure network connectivity, compared with the scheme which allows the usage of multiple types of channels. In addition, it can be seen that the ratio r remains almost constant as P_{bu} varies from 0.1 to 0.9. This means that the communication scheme which jointly use multiple types of channels works well in extremely hostile environment such as desert, where a large portion of sensors may be buried as time proceeds.

IV. CONCLUSION

In this paper, we perform topology analysis of WSNs for sandstorm monitoring. Specifically, the channel characteristics of four types of channels in the sandstorms are introduced. These channels include air-to-air (AA) channel, air-to-sand (AS) channel, sand-to-air (SA) channel, and sand-to-sand (SS) channel. By such channel diversity, the percolation-based connectivity analysis shows that for shallow burial depth, using multiple types of channels improves connectivity. Accordingly, it is shown that smaller sensor density is sufficient to achieve the same connectivity performance compared to the case where only a single communication medium, i.e., terrestrial air channel, is used.

REFERENCES

[1] I. F. Akyildiz and E. P. Stuntebeck. Wireless underground sensor networks: Research challenges. *Ad Hoc Networks (Elsevier)*, 4(6):669–686, 2006.

[2] I. F. Akyildiz, Z. Sun, and M. C. Vuran. Signal propagation techniques for wireless underground communication networks. *Physical Communication (Elsevier)*, 2(3):167–183, 2009.

[3] A. C. Balram and D. Dhar. Scaling relation for determining the critical threshold for continuum percolation of overlapping discs of two sizes. *Physics and Astronomy (PRAMANA)*, 74:109–114, 2010.

[4] O. Dousse, F. Baccelli, and P. Thiran. Impact of interferences on connectivity of ad hoc networks. *IEEE/ACM Transactions on Networking*, 13(2):425–436, 2005.

[5] J. Goldhirsh. Parameter review and assessment of attenuation and backscatter properties associated with dust storms over desert regions in the frequency range of 1 to 10 ghz. *IEEE Transactions on Antenna and Propagations*, 30:1121 – 1127, 1982.

[6] S. L. Gong and X. Y. Zhang. Cuace/dust - an integrated system of observation and modeling systems for operational dust forecasting in asia. *Atmos. Chem. Phys. Discuss.*, 7:10323–10342, 2007.

[7] O. Hggstrm, Y. Peres, and J. E. Steif. Dynamic percolation. *Ann. IHP Prob. et. Stat.*, 33:497–528, 1997.

[8] Z. Kong and E. M. Yeh. A distributed energy management algorithm for large-scale wireless sensor networks. In *Proc. of ACM MOBIHOC'07*, pages 209 – 218, 2007.

[9] R. Meester and R. Roy. *Continuum Percolation*. Cambridge University Press, New York, NY, USA, first edition, 1996.

[10] S. Nickovic, G. Kallos, A. Papadopoulos, and O. Kalaliagou. A model for prediction of desert dust cycle in the atmosphere. *J. Geophys. Res.*, 106:18113–18129, 2001.

[11] S. U. Park and H.-J. In. Parameterization of dust emission for the simulation of the yellow sand (asian dust) event observed in march 2002 in korea. *J. Geophys. Res.*, 108:4618, 2003.

[12] J. Quintanilla, S. Torquato, and R. M. Ziff. Efficient measurement of the percoaltion threshold for fully penetrable discs. *Physics A*, 86:399–407, 2000.

[13] A. R. Silva and M. C. Vuran. Communication with aboveground devices in wireless underground sensor networks: An empirical study. In *Proc. of IEEE ICC '10*, Cape Town, South Africa, May 2010.

[14] Z. Sun and I. F. Akyildiz. Connectivity in wireless underground sensor networks. In *Proc. of IEEE SECON 2010*, pages 1 – 9, 2010.