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Lifetime analysis of wireless sensor nodes in different smart grid environments

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Abstract Wireless sensor networks (WSNs) can help the realization of low-cost power grid automation systems where multi-functional sensor nodes can be used to monitor the critical parameters of smart grid components. The WSN-based smart grid applications include but not limited to load control, power system monitoring and control, fault diagnostics, power fraud detection, demand response, and distribution automation. However, the design and implementation of WSNs are constrained by energy resources. Sensor nodes have limited battery energy supply and accordingly, power aware communication protocols have been developed in order to address the energy consumption and prolong their lifetime. In this paper, the lifetime of wireless sensor nodes has been analyzed under different smart grid radio propagation environments, such as 500 kV substation, main power control room, and underground network transformer vaults. In particular, the effects of smart grid channel characteristics and radio parameters, such as path loss, shadowing, frame length and distance, on a wireless sensor node lifetime have been evaluated. Overall, the main objective of this paper is to help network designers quantifying the impact of the smart grid propagation environment and sensor radio characteristics on node lifetime in harsh smart grid environments.

Keywords Smart grid · Wireless sensor networks · Lifetime analysis

1 Introduction

Efficient transmission and distribution of electricity are fundamental requirements to provide services to societies and economies in the world. The need to renew power grids, meet growing demands for sustainable and clean electric energy presents major challenges. However, the increasing electricity demands all around the world, together with the complex nature of the power grid, cause congestion in the power grid, where the entire network capacity is limited by a few highly loaded power lines, while the rest of the network remains under-utilized [1–4]. Furthermore, the existing power grid suffers from the lack of efficient two-way communications, which also leads to blackouts due to the cascading effect initiated by a single fault [2, 5].

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To address all these challenges, a new concept of next generation electric power system, a smart grid, has been proposed [2]. The smart grid is a modern power grid infrastructure for enhanced reliability, productivity, and safety through automated controls and modern communication technologies. Considering the large scale of the electric power grid, low-cost monitoring and control enabled by real-time sensing technologies have become essential to maintain the efficiency of the smart grid.

With the recent advances in wireless sensor networks (WSNs), the realization of low-cost embedded power grid automation systems have become feasible. In these systems, wireless multi-functional sensor nodes have been used to monitor the critical parameters of smart grid components [6–9]. The WSN-based smart grid applications include power system monitoring and control, power fraud detection, demand response, load control, fault diagnostics and distribution automation [2, 10–13]. However, the design and implementation of WSNs are constrained by energy resources [14, 15]. In general, sensor nodes have limited battery energy supply and thus, communication protocols for WSNs are mainly tailored to provide high energy efficiency.

In this paper, the lifetime of wireless sensor nodes has been analyzed under different smart grid radio propagation environments, such as 500 kV substation, main power control room, and underground network transformer vaults. Although there exists sensor node lifetime analysis for different sensor hardware architectures, none of them addresses how different smart grid radio propagation environments affect the network lifetime of the corresponding smart grid application. Analyzing the lifetime of sensor nodes in terms of different radio and network parameters and smart grid spectrum characteristics gives a new impulse to ongoing research topics. Overall, the main objective of this paper is to help network designers quantifying the impact of the smart grid propagation environment and sensor radio characteristics on node lifetime in harsh smart grid environments. The main contributions of our study can be itemized as follows:

- The effects of smart grid channel characteristics and radio parameters, such as path loss, shadowing deviation, frame length and distance, on a wireless sensor node lifetime have been evaluated.
- The challenges on deploying schedule-driven wireless sensor networks in smart power grid environments have been explained to estimate the node lifetime.
- In addition to smart grid environment characteristics, the impact of different operation modes of sensor nodes on network lifetime has been discussed.

The remainder of this paper is organized as follows. In Sect. 2, we present an overview of the related work on wireless sensor node lifetime. In Sect. 3 we introduce the new method and protocol. In Sect. 4, we present the mathematical model and evaluate the performance of our solutions. Finally, we conclude the paper in Sect. 5.

2 Related work on lifetime estimation in wireless sensor networks

One of the major research activities within the area of wireless sensor networks was based on lifetime analysis in the last decade. In [16], a two sensor node network is modeled and trigger-driven and schedule-driven nodes, are analyzed for power consumption and the solutions are validated by using the simulation tool, MATSNL. Based on the work of [16], the lifetime is also taken into consideration within the context of availability and security in [17]. Alhtough the existing lifetime models are applicable in networks to meet certain specified conditions, they do not deal with how environmental spectrum characteristics affect the network lifetime and average power consumption per node. Wireless channel propagation characteristics are as much important as hardware specifications as stated in [18]. In order to conduct an accurate analysis, the power dissipation of a node should be analyzed by considering the wireless channel parameters.

Specifically, different deployment environments and indicative parameters are essential to analyze power consumption of a node. The main indicative parameters that affect sensor networks include network coverage, event detection ratio, quality of services parameters (QoS), connectivity (availability, latency, loss), requirements for continuous service (service disruptions up to a length) and the observation accuracy (measurement errors). Additional parameters, such as link asymmetry and channel characteristics, have been considered in our work to calculate more accurate power consumption of sensor nodes.

In recent years, existing platforms improved new techniques for reducing power leakage on sleep mode and dual pre-processor/radio architecture to analyze power efficient and high-power components as XYZ in [19], LEAP in [20], iMote2 in [21]. Moreover, an energy management and accounting preprocessor (EMAP) module enables to construct different power modes on sensors. In addition, the detailed simulation tool PowerTOSSIM computes the power consumption with a low error margin. In [22, 12], the schedule-based energy consumption is shown for target tracking application [23].

In [24], a demonstrator of a wireless sensor network for smart grid applications is introduced. It explains the hardware of the sensor nodes and demonstrates the results of the performance activity with the assurance of the feasibility of the recommended solutions. In [25] a system analysis is provided with a solution to the problem of controlling the sleep-awake period of nodes optimally. The proposed solution aims to extend the node life time as well as the network lifetime based on the constraint of the end-to-end packet delivery delay.

Although there exists sensor node lifetime analysis for different sensor hardware architectures, none of them addresses how different smart grid radio propagation environments affect the network lifetime of the corresponding smart grid application. Analyzing the lifetime of sensor nodes in terms of different radio and network parameters and smart grid spectrum characteristics gives a new impulse to ongoing research topics.

3 Evaluated methods and protocols

In the literature, different lifetime models, such as event-driven and schedule driven models, are used to evaluate the lifetimes of WSNs. In particular, a set of sensor hardware parameters, such as power consumption per task, state transition overhead and communication cost, are used to compute the average lifetime of a node for a given event arrival rate. In general, five different power states are commonly used for each lifetime model. In event-driven model, the pre-processor is always on and the node is in a deep sleep mode. The node is in the awake state if and only if an event is detected. In the schedule driven node, the duty cycle is described as awake time/duty period. The node is sleeping most of the time of operation and sleeps until the node wake-up timer expires. In our model, the power state transitions are described as a Semi-Markov chain and the following assumptions are made:

- The first-order statistical characteristic (mean value) of all random quantities (events, processing time, etc.) is known by observation and experiment.
- The processing and communication time is short compared to inter-arrival time of events. Processing and radio-transmission times are independent and identically distributed.
- The event duration is zero for an impulse event. We assume all events in the schedule-driven mode as an impulse event.
- The zero event durations make the duty cycle equal to the detection probability. The modulation scheme is orthogonal quadrature phase shift keying (O-QPSK). It is used in Telos with direct sequence spread spectrum (DSSS), which provides much more sophisticated mechanism for sensor networks [26, 12].
- CSMA MAC protocol is used to calculate the average power consumption of an individual packet transmission. During each communication period, the sensor resides in a limited number of low power states.

Table 1 Modes of a schedule-driven node

Modes	Sensor	CPU	Radio
S_0	Off	Off	Off
S_1	–	–	–
S_2	On	On	Off
S_3	On	On	T_x
S_4	On	Idle	Off
S_5	On	On	R_x

To model wireless channel in smart grid environments, we also used the wireless channel model and parameters determined in our previous study via field-test experiments [2]. In this model, signal to noise ratio $\gamma(d)$ at a distance d from the transmitter is given by the equation [27]:

$$\gamma(d)_{dB} = P_t - PL(d_0) - 10\eta \log_{10}\frac{d}{d_0} - X_\sigma - P_\eta \quad (1)$$

where P_t is the transmit power, $PL(d_0)$ is the path loss at a reference distance d_0, η is the path-loss exponent, X_σ is a zero mean Gaussian random variable with standard deviation σ and P_η is the noise power (noise floor), in which all powers are in dBm.

In this section, we investigate the lifetime of wireless sensor nodes in smart grid with respect to different power system environments. For the performance evaluation, we modified the Matlab simulation environment MATSNL [16, 28] to evaluate the effects of the propagation characteristics on node lifetime in different smart grid environments. The node is determined to work as a schedule-driven node in which its period of working is determined by a timer which indicates the time period as if the node is in the active mode $Timer_{awake}$ or in sleep mode $Timer_{sleep}$. Schedule-driven node working mechanism consists of six different modes as seen in Table 1. The smart grid channel parameters we used in our performance analysis are listed in Table 2 and the power consumption of each mode is presented in Table 3.

Importantly, according to the mode definitions, there should be more definitions stated in order to get an understanding of the whole picture of schedule-driven nodes. There are transitions between different states with certain probabilities. Demonstration of the power transition of a schedule-driven node, which is formed as Semi-Markov chain as shown in Fig. 1 helps to examine the power state transitions [16]. Beginning with the assumption that the node is awake, when if there is a β probability event present then it would be stated that the event would be detected.

As the next step, the sensor transits to S_{4e}, which is called as the monitoring state. In this case, the preprocessor and the sensor is working, CPU is idle and the radio component of the node is not in process After monitoring state, the mechanism would certainly transit to the processing state, S_2, which

Table 2 Path loss exponent and shadowing deviation in smart grid environments

Propagation environment	Path loss (η)	Shadowing deviation (σ)	Noise floor (P_n)
500 kV substation (LOS)	2.42	3.12	−93
500 kV substation (NLOS)	3.51	2.95	−93
Underground transformer vault (LOS)	1.45	2.45	−92
Underground transformer vault (NLOS)	3.15	3.19	−92
Main power room (LOS)	1.64	3.29	−88
Main power room (NLOS)	2.38	2.25	−88

forces the CPU to turn on. Following this state, the operating mode of the sensor is S_3 if the sensed event has data to be sent to the base station (BS) which has the α probability and the radio component turns on. On the other hand, if the probability 1-α happens to occur that the sensed event has no data to be transferred to BS, then the sensor node transits to the sleep state. Lastly, the data sent to BS is processed at the communication state and transition to sleep state with probability 1 which completes cycle of the Semi-Markov chain. In addition to the assumption that the node is awake 1-β is the probability when there is not any sensed event in the medium. In this case, the node transits to S_{4i} and in return, it transits back to the sleep state as $Timer_{sleep}$ takes over its duty.

Importantly, to get a better understanding of the mechanism of the schedule-driven mode node, the average consumed power should be examined. Since the consumed power is highly related to the detection probability of the events sensed in the medium, the mechanism is stated with comparison to trigger-driven mode node in terms of detection probability and average consumed power in [16]. As shown in Table 4, T_c indicates the duration of the duty cycle d, T_w shows the awake period of the node, whereas T_s shows the sleep period of the node and u is the detection probability of an event. Lastly, as mentioned before, λ indicates the poisson arrival rate of the events to the specified medium. The consumed power does not vary with the varying detection probability for the case trigger-driven mode nodes but on the contrary the power consumption of schedule-driven nodes changes because its transition mechanism is led by the timer. Overall, all the important parameters affecting sensor node lifetime are summarized in Table 4. In order to examine the average consumed power in a more detailed way, the related definitions are stated as follows:

- M_e is the residual energy that can be specified as the rest of the energy consumed in a cycle in which the node is awake. It can be formulated as:

  $$M_e = P_w * T_w - (T_w * (P_{s_2} + P_{s_3})) \tag{2}$$

  where P_w is the consumed power when the node is in the awake period, P_{s_2} is the power consumed in the processing state and P_{s_3} is the power consumed in the communication State.
- M_t is the residual time. In a cycle, the operation of a node takes a determined time and the rest time of the node is called as M_t, which is formulated as:

  $$M_t = T_w - (T_{s_2} + T_{s_3})/(T_{s_2}) \tag{3}$$

  where T_{s_2} is the time spent in the processing state and T_{s_3} is the time spent in the communication state.

Note that the major parameter that changes the node lifetime is the transmission power of the node, since the

Table 3 Schedule driven sensor node power specifications

Sensor	Mica2	Telos	Imote2	XYZ
Microcontroller	ATMega128	TIMSP430	PXA271	ML67 ARM/THUMB
CPU ON (mW)	24	2.7	193	41
CPU IDLE (mW)	9.6	0.09	88	34
CPU OFF (mW)	0.3	0.0018	1.8	0.0063
CPU wake up time (µs)	180	6	860.11	252
Radio	CC1000	CC2420	CC2420	CC2420
Tx	25.5	35	70	57
Rx	21	38	80	65
Idle	0.7	0.7	0.7	0.7
Wake up time(µs)	180,000	580	860	860
Data rate	38.4	250	250	250
Modulation	FSK	O-QPSK	O-QPSK	O-QPSK
Processing time	0.2	0.2	0.2	0.6

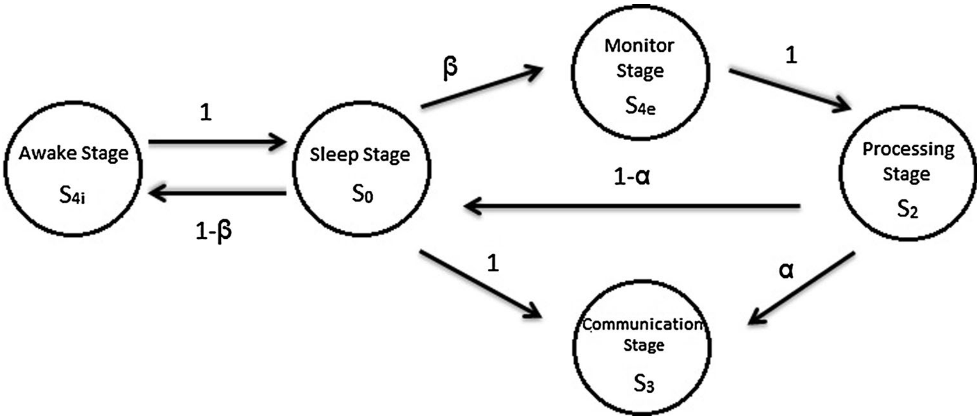

Fig. 1 Semi-Markov chain power state transition model of a schedule driven node

Table 4 List of simulation parameters

Parameter	Definition
β	Probability of an event present in the cell
d	Duty cycle
M_e	Residual energy
M_t	Residual time
P_w	Consumed power when the node is awake
P_e	Average power consumption when there is no events are detected
P_{s_2}	Consumed power in the processing state
P_{s_3}	Consumed power in the communication state
T_c	Duration of duty cycle
T_s	Sleep period of node
T_w	Awake period of node
T_{s_2}	Time spent in the processing state
T_{s_3}	Time spent in the communication state
N_{tx}	Number of retransmissions
T_L	Expected life time
u	Detection probability

power consumption during communication mode is very high compared to other operation modes. Moreover, when the channel conditions are bad and packet losses occur, the node retransmits the data packet to reliably transmit the message. All these retransmissions cause further power consumption for the sensor node. Therefore, to estimate the lifetime of a node accurately, the impact of radio propagation and environmental characteristics on packet reception rate should be considered. Here, the packet reception rate (PRR) represents the ratio of the number of successful packets to the total number of packets transmitted over a certain number of transmissions. Note that combining bit error rates together with the corresponding encoding schemes ; the packet reception rate (PRR) for different sensor motes can be calculated. It is also important to note that different from earlier platforms, the modulation scheme of the recent sensor node platforms is based on IEEE 802.15.4 standard, which uses orthogonal quadrature phase shift keying (O-QPSK) with direct sequence spread spectrum (DSSS), providing much more sophisticated mechanism for the sensor networks. For example, the modulation scheme used in Telos nodes is offset O-QPSK with DSSS. O-QPSK with DSSS modulation scheme in [29], where K is the number of users who are transmitting simultaneously and N is the number of chips per bit.

$$P_b^{OQPSK} = Q(\sqrt{((Eb/No)_{DS})}) \tag{4}$$

where

$$(Eb/No)_{DS} = \frac{(2N \times Eb/No)}{(N + 4Eb/No(K-1)/3)} \tag{5}$$

Combining the bit error rates together with the corresponding encoding scheme NRZ; the packet reception rate (PRR) for different sensor nodes can be calculated as shown in [27]:

$$PRR = (1 - P_b)^{8l}(1 - P_b)^{8(f-l)} \tag{6}$$

In the following section, considering all above-mentioned assumptions , we analyze the lifetime of wireless sensor nodes in smart grid environments based on smart grid channel characteristics (such as path loss, shadowing deviation, etc.), sensor operation states and modes, as well as network parameters (duty cycle, event arrival rate, packet reception rate, frame length and distance, etc.). Although there exists sensor node lifetime analysis for different sensor hardware architectures, none of them addresses how different smart grid radio propagation environments affect the network lifetime of the corresponding smart grid application. When considering the propagation characteristics, we believe that the researchers can achieve more accurate lifetime estimations. Thus, analyzing the lifetime of sensor nodes in terms of different radio and network parameters and smart grid spectrum characteristics will give a new impulse to ongoing research topics.

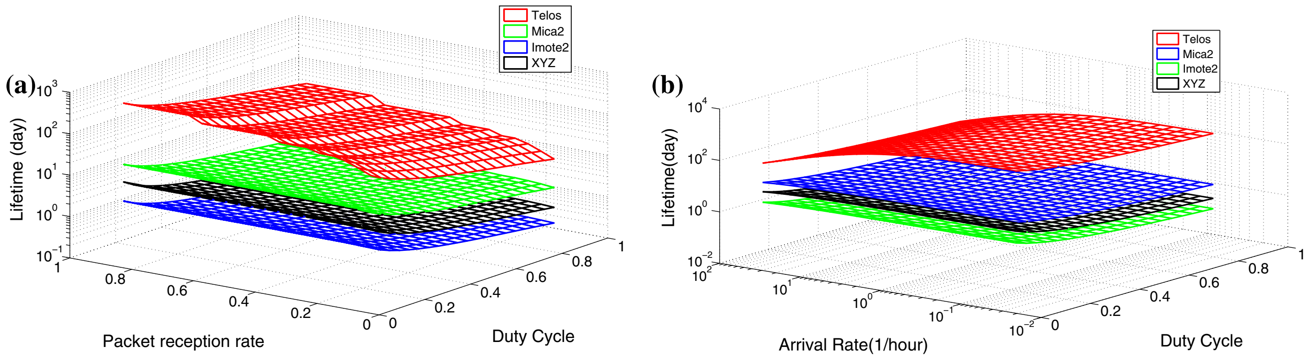

Fig. 2 **a** Packet reception rate versus duty cycle versus life time analysis. **b** Arrival rate versus duty cycle versus life time

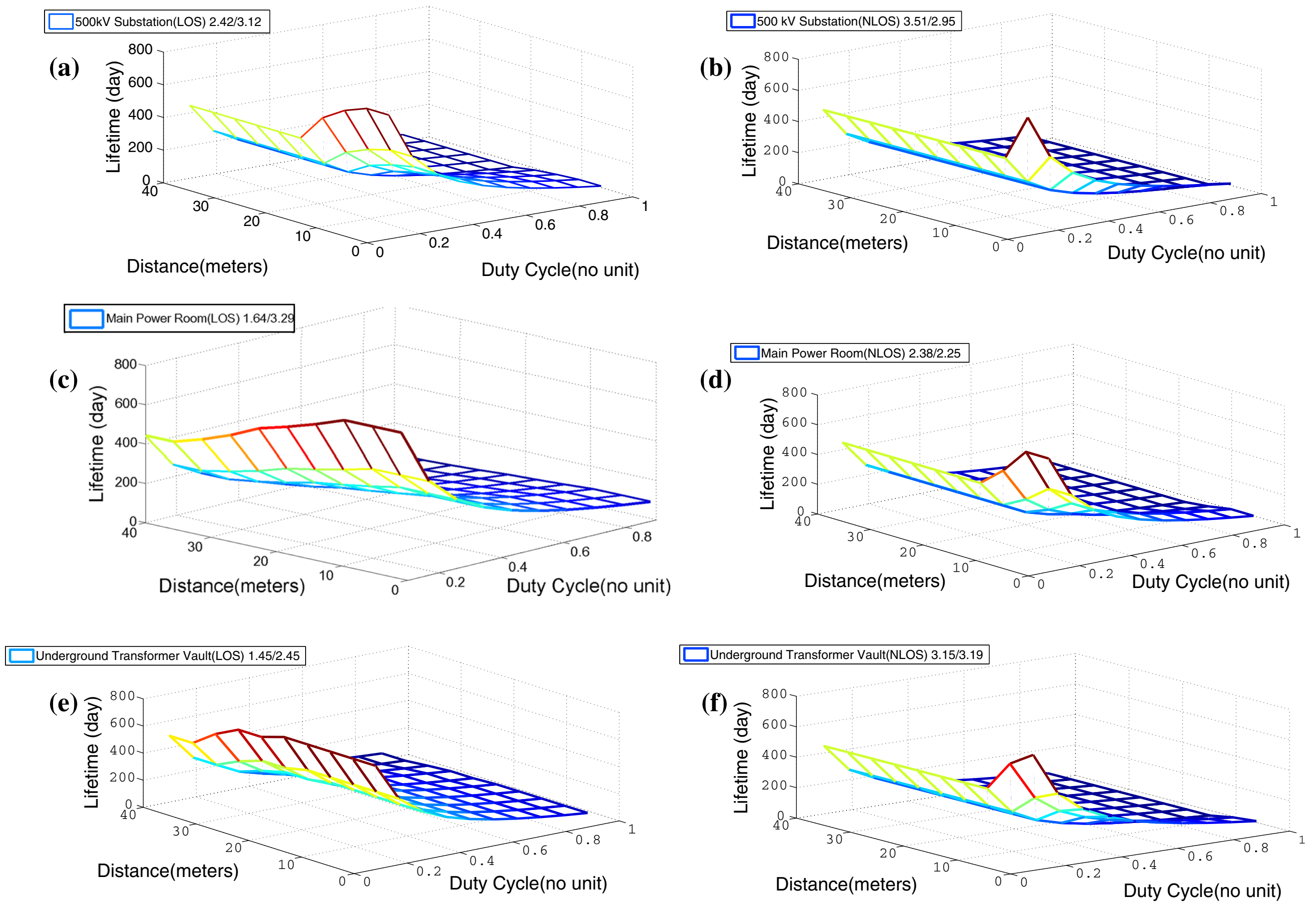

Fig. 3 Lifetime versus distance analysis in experimental smart grid sites. **a** Outdoor 500-kV substation environment (LOS), **b** outdoor 500-kV substation environment (NLOS), **c** main power room (LOS), **d** main power room (NLOS), **e** underground transformer vault (LOS), and **f** underground transformer vault (NLOS) transformer vault environments

4 Performance evaluations

Our performance evaluation is based on experimentally determined lognormal channel parameters from our previous work [2], where the wireless channel in different smart grid environments was modeled through real-world field tests by using the IEEE 802.15.4 compliant wireless sensor nodes in different electric power system environments such as such as 500 kV substation, main power control room, and underground network transformer vaults.

We compared lifetime of a schedule-driven Telos under six different smart grid environments. In Fig. 2(a), (b), we

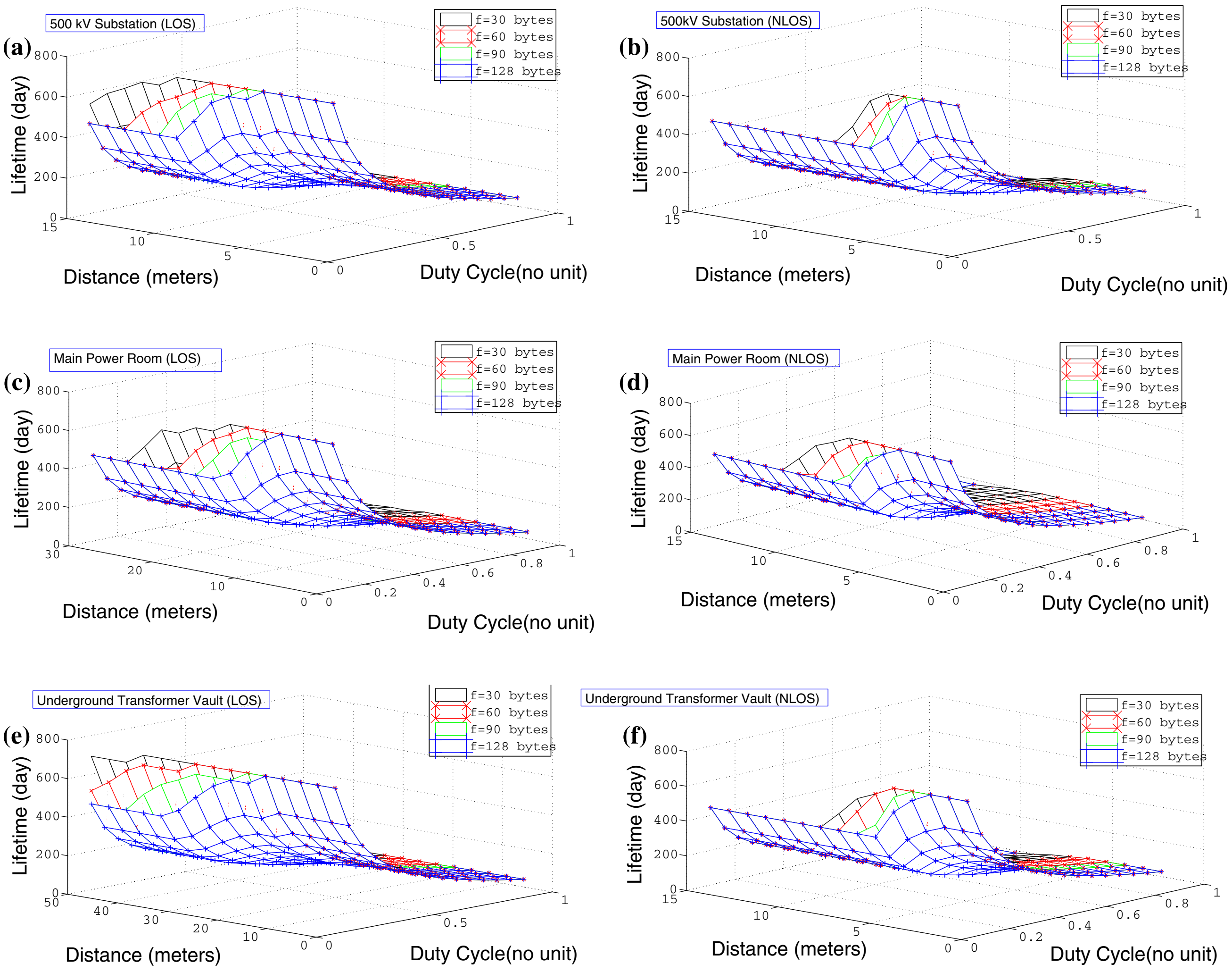

Fig. 4 Observation of the node lifetime for six different smart grid site. **a** Outdoor 500-kV substation environment (LOS), **b** outdoor 500-kV substation environment (NLOS), **c** underground transformer vault (LOS), **d** underground transformer vault (NLOS), **e** main power room (LOS), and **f** main power room (NLOS)

observe that the increasing distance at a fixed value of a duty period, decreases the lifetime. In these figures, we see that increasing the arrival rate and duty cycle decreases the lifetime of different nodes, since the event detection probability increases during the awake period at each node. We also observed that the maximum lifetime is obtained from Telos node due to its low energy consumption in both processing and idle stages compared to other sensor nodes. Note that Mica2, XYZ and Imote2 consume much more power in processing and idle stages. The lifetime duration of Mica2 suffers from the wake up time, which is too high compared to other nodes.

In the following, we continue our lifetime evaluations with Telos nodes, since it has longer lifetime compared to other nodes. As shown in Fig. 3(a)–(f), increasing duty cycle decreases lifetime exponentially, since the node is continuously sampling during the awake period. Increasing duty period in WSNs exponentially decreases the network lifetime. Additionally, we show the network lifetime with varying communication distance and duty cycle for different smart grid environments. In these figures, we see that the maximum lifetime of a node is around 835 days. In addition, increasing inter arrival rate with a duty cycle (increasing the awake time during duty period) decreases the lifetime of the node, since the detection probability of the awake node becomes higher. The high detection probabilities consume more power as compared to lower duty cycles.

In addition, we observe that as the length of the frame increases, the lifetime of the node exponentially decreases in a fixed inter-arrival time in Fig. 4(a)–(f). At a fixed inter-arrival time, we see that the average power dissipation is increasing with retransmissions due to the radio environment. In order to evaluate the effects of the frame length on the lifetime, we used SNR values that affect the packet reception rate and life time eventually. In general increasing the SNR value, small size of frame length increases packet reception rate compared to large size of frame lengths.

In summary, our performance evaluation demonstrates that the smart grid channel parameters, such as path loss exponent and shadowing, directly affect the lifetime of a schedule-driven node in smart grid environments. We compared the lifetime of a schedule-driven Telos in six different smart grid environments. The overall lifetime of the network is vulnerable for the propagation characteristics of the smart grid environment. As shown in the above mentioned figures, increasing the duty cycle decreases the lifetime exponentially, since the node is continuously sampling during the awake period in terms of detection probability of an event. Without considering the channel conditions, the lifetime is only related to duty cycle, duty period and arrival time of events. While considering the propagation characteristics, we believe that the researchers can achieve more accurate lifetime estimations. We calculate the lifetime by considering the packet reception rates, which affect the total number of transmitted packets per sensed event. Increasing the distance among nodes decreases the received power of the signal, which decreases exponentially with increasing path loss exponent. We also observe that the lifetime changes due to channel conditions in different environments. Furthermore, the high path loss environments have a negative impact on the network lifetime.

5 Conclusions

With the recent advances in wireless sensor networks (WSNs), the realization of low-cost embedded power grid automation systems have become feasible. In these systems, wireless multi-functional sensor nodes have been used to monitor the critical parameters of smart grid components. The WSN-based smart grid applications include power fraud detection, demand response, power system monitoring and control, load control, fault diagnostics and distribution automation. However, the design and implementation of WSNs are constrained by energy resources. In general, sensor nodes have limited battery energy supply and thus, communication protocols for WSNs are mainly tailored to provide high energy efficiency. In this paper, the lifetime of wireless sensor nodes has been analyzed under different smart grid radio propagation environments, such as 500 kV substation, main power control room, and underground network transformer vaults. Specifically, sensor node lifetime is analyzed in terms of smart grid channel characteristics (such as path loss, shadowing deviation, etc.), sensor operation states and modes, as well as network parameters (duty cycle, event arrival rate, packet reception rate, frame length and distance, etc.). Although there exists sensor node lifetime analysis for different sensor hardware architectures, none of them addresses how different smart grid radio propagation environments affect the network lifetime of the corresponding smart grid application. Overall, the main objective of this paper is to help network designers quantifying the impact of the smart grid propagation environment and sensor radio characteristics on node lifetime in harsh smart grid environments.

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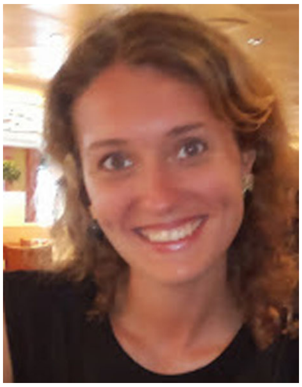

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