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Evaluation of a duty-cycled asynchronous X-MAC protocol for vehicular sensor networks

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Abstract

An asynchronous medium access control (MAC) duty-cycled protocols have higher energy efficiency and lower packet latency than synchronized ones due to reduced idle listening. Moreover, they provide efficient utilization of energy supplied to mobile sensors. They are considered very important in MAC protocols due to the adverse effects of hidden terminals which causes energy consumption in sensor networks. Therefore, in this paper, the impact of hidden terminals on the performance of an asynchronous duty-cycled MAC protocol X-MAC for vehicle-base sensor is investigated via analysis and simulations. We propose a Markov model to analyze the quality-of-service (QoS) parameters in terms of energy consumption, delay, and throughput. Our analytical model provides QoS parameter values that closely match the simulation results under various network conditions. Our model is more computationally efficient and provides accurate results quickly compared with simulations. More importantly, our model enables the designers to obtain a better understanding of the effects of different numbers of mobile sensor nodes and data arrival rates on the performance of an asynchronous MAC duty-cycled protocol.

Keywords: X-MAC, Markov model, Quality-of-service analysis

1 Introduction

Vehicular sensor networks (VSNs) allow limited range sensor devices to communicate with each other [1]. VSNs are promising solutions for specific cases of the Internet of things (IoTs), which allow the integration of different objects to communicate with each other in dynamic environments [2]. The current trends in VSNs allow different deployment architectures for vehicular networks in highways, urban, and rural environments to support many applications with different QoS requirements [3]. Basically, VSNs came to allow the communication among nearby vehicles as well as fixed roadside equipments which leads to three different configures: vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and, hybrid networks' architectures as illustrated in Fig. 1 [4]. Features of these configurations encounter new challenges in order to expand from being a network of computers to a network of both computers and things.

Devices in the IoT connect with each other using a variety of protocols, and there still exist a large amount of devices that use older communication protocols but have diverse real-time needs. Therefore, VSNs offers integrated communication protocols for effectively monitoring the physical world, especially in urban areas where a high concentration of vehicles equipped with onboard sensors is expected [5, 6]. Despite this, integration have benefits such as increasing revenue, reducing costs, and energy efficiency. However, there exists a serious problem with traffic congestion in decision making for vehicular traffic which is a challenge due to the particular characteristics, such as the highly dynamic topology and the intermittent connectivity [4]. Consequently, VSN has challenges in supporting the real-time traffic information that can significantly improve the safety of the transportation and can reduce the traffic congestion [7]. This information will help drivers to make smarter decisions in timely manner to prevent accidents, improve the efficiency of the selected route, and provide a safer distance among other vehicles. Therefore, the duty of the embedded sensor is to capture images and measure distance all around a vehicle in order to monitor traffic in an allocated area, while utilizing different devices that can measure several physical traffic parameters [5]. Hence, the view of the vehicle as a sensor platform can improve the traffic flow, via supporting

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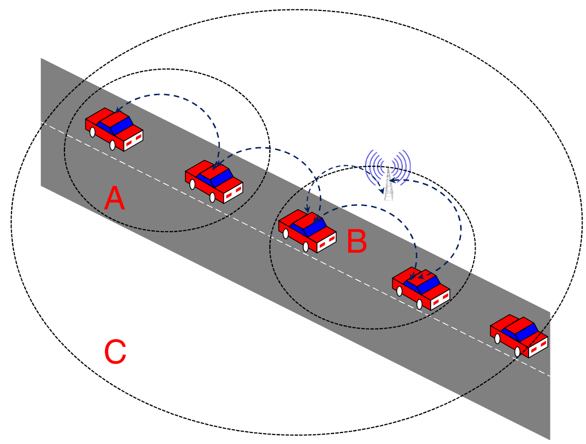

Fig. 1 Basic architecture of VSNs, **a** vehicle-to-vehicle (V2V), **b** vehicle-to-infrastructure (V2I), **c** hybrid

communication with the roadside infrastructure in order to provide ubiquitous coverage [8]. The relative velocities of vehicles are fairly much higher in than 50 km/h in urban environments and more than 100 km/h on the highway [4]. Vehicles also move at different directions. Thus, vehicles can quickly access or leave the network in a very short period of time. This results in more frequent changes in the network topology which affects the network design significantly. For example, the routing protocol design will be more difficult due to hidden/exposed terminal problem in MAC protocols [9]. Vehicles are typically not affected by strict energy constraints and can be easily equipped with sensor platforms [10]. Meanwhile, VSNs represent a significantly novel and challenging deployment scenario, which considerably differs from the traditional Wireless Sensor Network (WSN) and thus requires innovative solutions in the MAC layer [11]. However, designing an integrated architecture for both WSNs and VSNs often starts with the definition of a MAC protocol since it is a fundamental issue in determining the energy consumption properties and the basic data transport capabilities of the network [12].

This design of an efficient and effective sensory MAC protocol providing QoS requirements for real-time traffic management is considered as the most important step in end-to-end QoS provisioning over VSNs [13] since it regulates nodes' access to a shared channel and has become a major active research in recent years [14]. This regulation explicates as duty cycling approach that is considered as one of the primary mechanisms for providing QoS in VSNs [15].

Particularly, duty cycling means that every node in the network is periodically alternating between an awake and a sleep state [16]. Therefore, the duration of a duty cycle is equivalent to the time of an awake state plus the time of sleep state [17]. Whereas the idle state has been founded in IEEE 802.11p standard for vehicular communication that consumes substantial energy to transmit up to 1000 messages with 32 dBm and therefore should be avoided in VSNs [4].

To understand the performance of VSNs and in order to optimize the designed routing protocol [18], an accurate analytical framework for MAC protocol is required. The main idea of this framework provides an analytical scheme that dynamically adapt the vehicles' rate of transmission according to their priority. The analytical model shall describe the effects of assigning various values including the density and transmission range of vehicle to protocol parameter under given specific scenarios in order to achieve the QoS requirements.

The remainder of the paper is organized as follows: section 2 discusses some related works devoted entirely to analytical modeling of MAC protocols. Section 3 introduces the synchronous X-MAC protocol, through overview of problem definition of hidden terminal and analyzing power consumption, delay, and network throughput. Section 4 introduces the behavior of X-MAC protocol under specific network conditions through using the proposed Markov model. Meanwhile section 5 introduces the performance analysis of synchronized X-MAC protocol. Furthermore, section 6 introduces detailed simulation and analysis for the performance of a synchronized X-MAC protocol of various scenarios. Finally, section 7 concludes the current.

2 Related works

To better understand the mechanism of a MAC protocol, it is useful to realize that MAC protocols consists usually of three main logical components [19]. First, a collision avoidance (CA) algorithm which uses physical carrier-sensing to register and/or reserve the channel for the duration of the data transmission. Second, a contention resolution algorithm which uses mechanisms such as back-off to regulate the access to the channel [19]. Third, distributed coordination function (DCF) which is not specifically designed for high mobility network [7].

Various MAC protocols have been proposed to mitigate the adverse effects of hidden terminals through CA, since the hidden problem has demonstrated its energy-saving capabilities [11]. However, in a heterogeneous wireless networks, a hidden problem should be defined as a node out of the range of the sender which covers the receiver. Most CA algorithms are based on sender-initiated, including an exchange of short request-to-send (RTS) and clear-to-send (CTS) messages between a pair of sending and receiving nodes before the transmissions of the actual data packet and the optional acknowledgment packet [8]. Whereas in receiver-initiated, a receiver broadcasts a probing packets whenever it wakes up from sleeping state, while a sender with data packet to transmit waits in the listening state until the probing packets from the receiver is received. Therefore, receiver-initiated MAC protocol degrades the network performance with asymmetric links, due to several experienced sender failures in receiving the probing packets from the receiver. And hence, the asymmetric links waste energy, increase delay, and degrade the packet receive ratio (PRR). Meanwhile, RTS and CTS message exchange mechanism could not be the solution for VSNs since these exchange messages may not be able to arrive to all hidden nodes [20].

MAC protocols can be divided into two main categories of duty-cycled MAC protocols [17]. One is synchronized protocols, like S-MAC [21] and T-MAC [22]. The other is asynchronous protocols, like X-MAC [17] and B-MAC [23]. Asynchronous duty-cycled MAC protocols remove the energy overhead for synchronization and are easier to implement as they do not require local synchronization [24]. X-MAC protocol uses data packets as preambles and suits it for sparse networks as the energy and collision increase linearly with the node density. And thus, the performance of X-MAC protocol is evaluated in this work when equipped with CA algorithm to address the performance degradation of wireless multihop communications with hidden terminals, and their impact on MAC protocols. Additionally, the X-MAC contention-based protocol does not perform well in asymmetric scenarios due to the quality of the link from the receiver to the sender which causes the hidden terminal problems and can be avoided if the communication was not receiver-initiated [25].

Many researchers evaluated the performance of various network protocols through simulations [26]. However, the simulation environment/software is usually too expensive and/or time-consuming, especially while considering a huge network size/capacity [27]. Meanwhile, the analytical models can be more effective in such cases, since the scale of modern networks and the degree of complexity often necessitate the use of simplified assumptions, e.g., Markov, Poisson traffic, or other models. Furthermore, it is hard to capture the dynamic nature of a network without an analytical model; therefore, an analytical model is needed to provide insight into the performance of both routing and MAC protocols [27].

Bianchi [28] proposed an accurate analytical model to analyze the performance of single-hop IEEE 802.11. Ziouva [28] improved Bianchi's model by adding a deriving saturation delay beside throughput. In an area other than IEEE 802.11 specifically in WSNs the author in [29] proposed a radio model to compute the lower bound of X-MAC protocol. A new hybrid MAC scheme called Zebra MAC (ZMAC) is proposed in [30] for sensor networks which combine the strengths of TDMA and CSMA while offsetting their weaknesses. The authors in [31] implements an efficient TDMA protocol that apply duty-cycling function for multihop WSNs using semi-Markov chain. Authors tries to avoid channel access problems such as over hearing and hidden terminal by adapting the wakeup/sleep state of each node to the actual operational conditions such as traffic demand and node density. Short range V2V communication was investigated in [32]. The authors present a study in which effective information such as the message size, transmission range, and velocity of vehicles is exchanged. Such exchanged parameters are considered as factors in analytical model to evaluate the performance of communication. Meanwhile, the authors in [33] presents a study of connectivity in vehicular ad hoc network in traffic free-flow. Actually, the authors use the analytical model in describing the distribution of distances between the vehicles, traffic flow on the highway to evaluate the effects of various system's parameters (such as distribution of velocity, traffic flow, and transmission range of vehicles) the network on connectivity.

B-MAC [23] considers the default MAC protocol for Mica2 that allows an application to implement its own MAC through a well-defined interface. To achieve channel utilization and low power operations, the authors adopt low power listening (LPL) and scheduling the clear channel sensing (CCA) technique to reduce duty cycle and to minimize idle listening. Yang in [34] modeled and analyzed the throughput of a synchronized duty-cycle S-MAC protocol for WSNs. S-MAC protocol has different rules for accessing the media as compared against other MAC protocols such as X-MAC or B-MAC. Yang also proposed a Markov model to analyze the throughput of X-MAC. It should be emphasized that our proposed model is fundamentally different from the one proposed by Yang [29]. Our proposed model analyzes the performance of X-MAC protocol when it is equipped with CA algorithm and aimed of addressing the performance degradation of VSNs with hidden terminal. However, none included the hidden terminal problem in their analytical models. The paper focuses on the evaluate of an adaptive energy-efficient X-MAC protocol for duty-cycled VSNs. A Markov queuing model is proposed for modeling the behavior of the X-MAC contention based on the specific sleep/wake-up pattern in the duty cycle. Our proposed model quantifies the desirable QoS metrics for contention-based MAC protocols in multihop fashion to address the hidden terminal problem and to provide fairness in medium sharing among the vehicles.

3 Overview of X-MAC protocol

Asynchronous protocols have is promising applications in WSNs since they avoid synchronization overhead, and hence provide higher energy efficiency than synchronized

MAC protocols [29]. Many variations asynchronous duty-cycled MAC protocols have been proposed to improve energy efficiency and packet latency by allowing each node to independently and periodically sleep to save energy [35]. Additionally, asynchronous protocols use a series of short preamble packets to avoid synchronous overheads and hence have higher energy efficiency than synchronized MAC protocols [36]. These short preamble packets carry the address information of the sink node. As a results the intermediate nodes can go to sleep as soon as they hear the first short preamble. Moreover, the sink can reply with an ACK message in between two successive short preambles to stop the timeline and to start transfering the data packets [17].

Figure 2 indicates the timelines' LPL of short preamble packets of X-MAC protocol that effectively constitutes a single long preamble [17]. Whereas a node wakes up periodically to send and receive a short preamble packet to sink node which is still sleeping, it looks at the ID of sink node included in the packet. If the other nodes are not the intended recipient, they go to sleep quickly to avoid the overhearing problem; otherwise, they remain awake for the subsequent packet. Hence, the interval between two successive wake-up periods called a cycle denoted as T for every node. Every node begins its duty with a fixed-cycle length determined with an arbitrary offset and continues its duty cycling as if the medium had been idle. For each successfully delivered data packet, the average communication time is $\frac{T}{2}$ pulsing the length of data packet L_{DATA} [29].

X-MAC also has collision related within increasing the network density, i.e., the number of senders increases, and they wake up and begin to send their preamble at the same time since. Thus, all nodes including sink-nodes cannot determine the destination address information in preamble when collision occurs among nodes. In this case, the sender continues sending preambles until next wake-up time [17]. Hence, for each colliding data packet, the average communication of sending data packet is also T.

This paper proposes a mathematical model for X-MAC protocol which to includes the effects of CA algorithm. Our proposed model focuses onto two main contributions which are: (1) solving the problem of medium contention such as hidden or exposed terminal problem, and (2) providing resource reservation for real-time traffic control system in a distributed vehicle-based sensor environment. Moreover, supporting QoS in the routing or transport layer cannot be provided unless the assumption of MAC protocols solves the problems of medium contention and supports reliable communication [37].

Our proposed model acts as analyzer for the performance of X-MAC since the Markov model is used to

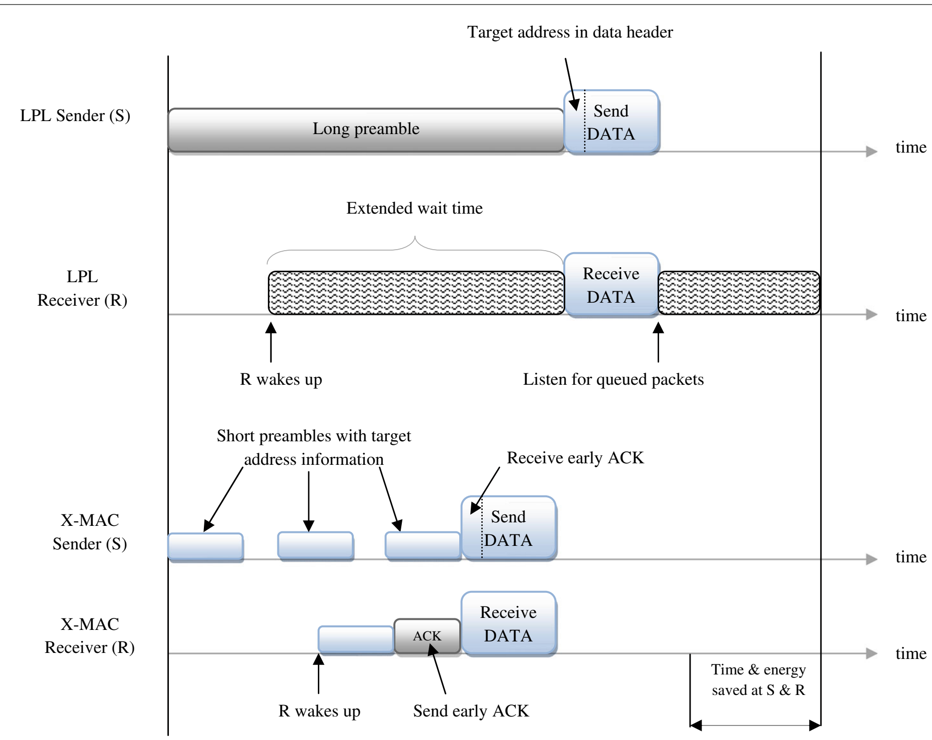

Fig. 2 The timelines LPL and X-MAC protocol for the short preamble approach [13]

describe the behavior of accessing of synchronized duty-nodes to the channel. The proposed model elaborates on which type of low duty-cycled MAC protocols should be selected in order to resource the wireless channel reservation that assures the desirable QoS level in real-time traffic control systems.

4 Markov model of X-MAC

We propose a Markov model to describe the behavior of X-MAC and investigate the QoS parameters under various network and channel conditions. However, to estimate the effect of the hidden problem, it is necessary to examine the transmission among one-hop neighbor nodes at region where possible hidden problem occurs as depicted in Fig. 3 in which node A transmits a frame to node B, and node D transmits to node B. Thus, node D will be able to do it, as it is unable to detect the transmission of node A or node C. This means that both nodes C and D are hidden to each other resulting in a collision at node B that causes a serious QoS degradation especially in high-data-rate sensor applications [29, 38].

In order to satisfy the QoS requirements for real-time traffic control systems, a Markov discrete-time stochastic process M/M/1 queuing model is proposed under realistic conditions for duty cycling with schedule-driven operation in VSNs. We consider a simple traffic model for vehicle moving along a straight road with random velocity. The arrival and departure of the data packets are regulated under a realistic assumption of a finite queue size. Therefore, the proposed model makes the following assumptions:

1. Event arrivals denote a stochastic process $\{A(t)|t \geq 0\}$ that represents the total number of arrivals that have occurred from time 0 to time t; this procedure creates an independent Poisson process at each node, and the number of packet arrivals in any time slot is distributed with a Poisson process with parameter $\lambda\tau$, for time of arrival $t\ \tau \geq 0$.
2. Let $\pi_\imath(t)$ denote the steady state of power for the node at time t; the inter-arrival $\delta \geq 0$ times (that is, the distribution of time at state $\imath$ before marking the transition) are independent and exponentially distributed with the λ, where $o(\delta)$ is defined as a function of δ such that $\lim_{\delta \longrightarrow 0} \frac{o(\delta)}{\delta}$.
3. The queueing discipline of data packets is first-come, first-served (FCFS).
4. The queueing system assumes equilibrium under the condition that the probability of arrival is less than the independent probability of transmitting the information packet or $\lambda < \beta$.
5. The processing and radio-transmission times are independent and identical ($\imath.\imath.d.$) with an arbitrary distribution.
6. Retransmission is supported.
7. When an event is sensed, the node processes it and sends the information packet with a probability of transmission per node per cycle, and every sensor node in the network has an independent probability of transmitting information packet β in the duty cycle.

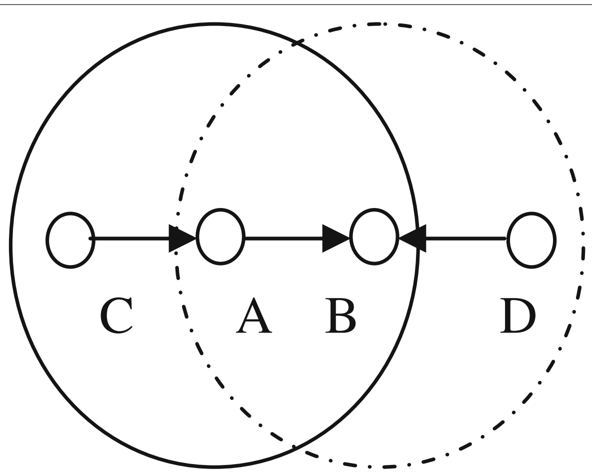

Fig. 3 Hidden terminal problem in contention-based protocols

These assumptions are made based on [39] which have been verified as valid approximations of realistic scenarios. The proposed Markov model shows that the power transition of each sensor node in the network may be modeled by a discrete-time M/M/1 Markov chain, which represents a different predefined status for a node for an event at the wake-up/sleep mode of the duty cycle. The proposed model considers the following assumptions:

(a) The vehicles are equipped with sensor nodes in a network and are assumed to be two-dimensionally Poisson distributed over a domain with density ρ. Therefore, the probability of finding n neighboring nodes in an area S is given by [34].

$$p(n, S) = \frac{(\rho S)^n}{n!} \exp^{(-\rho S)} . \tag{1}$$

(b) If each node has the same transmission range T_R for transmission and receiving in time-slotted mode, then the number of n neighbors within a circular region of T_R is given as [40].

$$n = \rho\pi T_R. \tag{2}$$

(c) All nodes are assumed to be saturated, i.e., they always have some data packet in queue waiting for transmission, and all the data packets have the same length.

(d) The time step value T is assumed not just the propagation delay, but also the transmission delays (SYNC, RTS, CTS, DATA, and ACK), processing delay, carrier sense delay and queuing delay.

(e) Each sensor node has transmission range T_R defined as [38]

$$T_R = \sqrt[\beta]{\frac{G_t G_t \lambda^2 P_{tx}}{\alpha Sen}}, \tag{3}$$

T_S is sensing range, and the interference range is defined as $T_I = T_R \sqrt[\beta]{TR_{CP}}$, where TR_{CP} and Sen are defined threshold of capture ratio, and the receive sensitivity in Watt, respectively [38].

(f) The propagation model is defined as

$$P_{tx} = Sen\left[\frac{G_t G_t \gamma^2}{(4\pi)^2 d^\beta}\right], \tag{4}$$

and

$$P_{\mathrm{rx}} = \frac{P_{\mathrm{tx}}}{\alpha d^\beta}, \tag{5}$$

where d defined the distance between two transmission nodes. This model cover with free-space model is defined by

$$\alpha = \frac{(4\pi)^2}{\omega^2 G_t G_t}, \tag{6}$$

where both G_t and G_r are defined by the antenna gain, γ is the wavelength, and β is defined by the path-loss exponent [38].

Table 1 lists all assumption that are used throughout the paper.

A node may exchange its status slot by slot, which corresponds to the transition from one state to another in the Markov chain as depicted in Fig. 4a. Figure 4b shows that the proposed Markov model has limited queuing capacity denoted as M with finite state slots from left to right, which corresponds to 0 state for processing packets in the queue and so on to m packets in the queue (full queue). Specifically, if a packet arrives and the queue is full, then the packet is simply dropped; nevertheless, the packets are removed from the queue when they are successfully transmitted. By contrast, when the queue is neither full nor empty, then a node may obtain access to the media to transmit packets with an independent probability. The analysis of the Markov discrete-time M/M/1 queuing model offers insights into the traffic behavior of vehicle-based sensor networks in general and points to an idea for a control algorithm.

The steady state probability and the transition probabilities of moving from one state to another can be described as follows:

$$P_{0,\imath} = \lambda_\imath \delta,\ \imath = 0, \ldots, M, \tag{7a}$$

$$P_{0,\imath} = A_\imath, \imath = 0, \ldots, M, \tag{7b}$$

Table 1 Assumptions

Symbol	Quantity
N	Number of nodes in the network
T	Length of a cycle
W	Contention window size in units of a time slot
M	Queue capacity in units of a data packet
m	Number of data packet in queue
S	Data packet size
$\imath, \jmath$	the state of node
$P_{\imath,\jmath}$	the probability of transition from state $\imath$ to state $\jmath$ for the node
p_f	Probability of transmission failure of data packet
p_s	Probability of successfully transmission of data packet
n	Number of sensor nodes in specified area
ρ	Density of sensor nodes
T_r	Transmission range
T_s	Sensing range
T_I	Interference range
λ	Expected data packet arrival rate at the MAC layer
$A_\imath$	Probability of $\imath$ data packets arriving in a cycle
π	The stationary distribution of the Markov model
τ	The probability of an arbitrary node transmitting in time slot
D	Packet delay

$$P_{0,M} = A_{\geq M}, \tag{7c}$$

$$P_{\imath,\imath-1} = p_s A_0, \imath = 0, \ldots, M. \tag{7d}$$

$$P_{\imath,\imath-1} = p_s A_{\jmath-\imath+1} + (1-p_s)A_{\jmath-\imath}, \imath = 1, \ldots, M-1. \tag{7e}$$

$$P_{\imath,M} = p_s A_{\geq M-\imath+1} + (1-p_s)A_{\geq M-\imath},\ \imath = 1, \ldots, M. \tag{7f}$$

$$P_{\imath,\jmath} = 0, \imath = 2, \ldots, M, \jmath = 0, \ldots, \imath-2, \tag{7g}$$

If an abnormal event of interest is detected during the specified operations, then Eqs. 7a and 7b describe all transitions from an empty-queue status to a non-empty status according to the Poisson process probability of new packet arrival λ. The typical schedule-driven operation for vehicle-based sensor node operates with two timers: one for the wake-up mode and another for sleep mode, for each node in the network [37]. Therefore, if an abnormal event is detected by a sensor node and needs to be transmitted to another node or to the sink, the node stops the sleep-mode timer, turns on its radio, and starts processing the event; otherwise, the node remains in sleep mode. Equations 7c and 7f describe the transition probability of

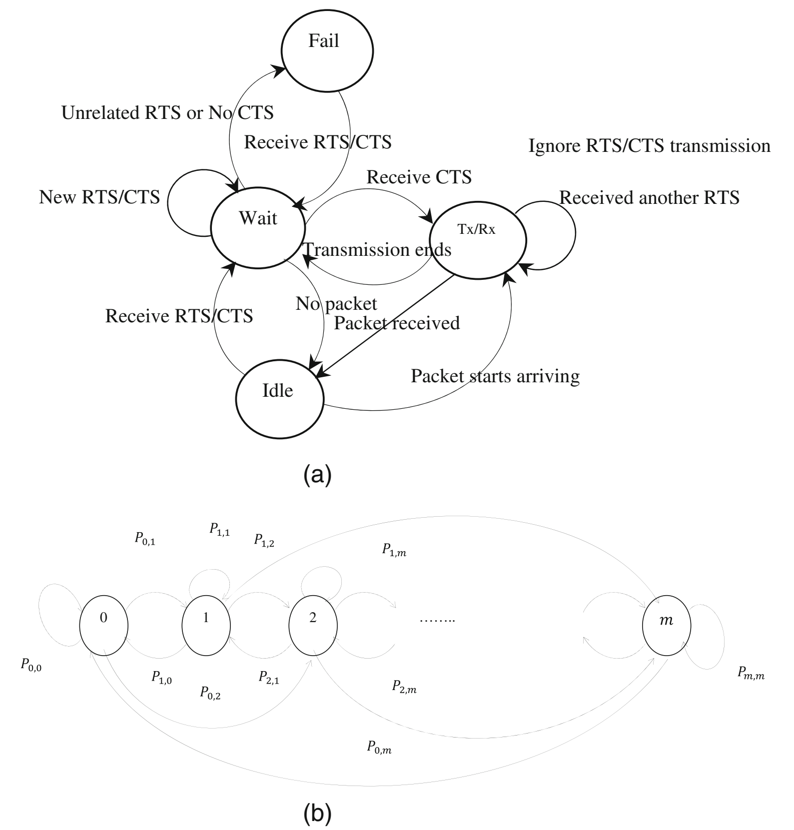

Fig. 4 Markov model for the X-MAC protocol and node. **a** Markov chain model for a node, (**b**) Markov chain model for X-MAC

the schedule-driven duty-cycle node operation, including the processing and transmission of information packets.

Equations 7d and 7e also describe the non-transition probability state (i.e., the probability of having a non-decreasing queue), which can be obtained from two terms depending on the oldest information packets still in the queue and winning the contention to access the media (first term) or otherwise (second term) [35, 38].

4.1 The hidden problem formulation

According to the heavy-traffic assumption [41], each node in the network always has a packet in its buffer to be sent. Suppose a node is ready to transmit with probability p_s, the probability of collision is p_f, A_ι defines the probability that ι of data packet arrives at node during a cycle, and $A_{\geq\iota}$ is the probability that no less than ι data packets arrive at a node during a cycle. Then, p_s is considered as a protocol-specific parameter that is slot independent. This means that the probability of transmission and the collision varies from another time slot, depending on the behavior of both duty-cycled node which modeled as Markov-chain and the state of channel which is depicted in Fig. 4, where π_0 indicate the steady state of a node. Because of a node may transmit or not in the slot depending to the mechanism that is used to avoid and resolve the collision as well as the current state of the channel [39]. Therefore, there is an exact relationship between p_s and p_f and should be derive to investigate the effects of p_s and p_f on performance of multihop network.

Generally, for single-hop IEEE 802.11, Bianchi [28] has proposed a multi-dimensional Markov chain-model to derive the probability of successful packet transmission as a node always has a packet in its buffer ready to send and that the next hop is randomly selected as

$$p_s(p_f) = \frac{2}{1 + W + p_f W \frac{(2p_f)^m - 1}{2p_f - 1}} \tag{8}$$

where W is the minimum contention window size and m is the retry limit. Suppose that the sensor node is in a steady state, then the probability of an arbitrary sensor node transmitting in time slot denoted by τ is [42].

$$\tau = \frac{p_s T}{D}, \tag{9}$$

$$D = \lambda + p_s T_{\text{tran}} + Y \tag{10}$$

where λ defines the average event inter arrival rate, T_{tran} is the transmission time, and Y defines the processing time per event.

In general ,τ depends on the conditional transmission probability p_s and collision probability p_f, which is still unknown as shown in Eq. 3. Therefore, to find the value τ, it should be first assumed successfully received value as the probability that only one node of the n neighboring nodes is transmitting [43]. Because each node n transmits with probability τ, therefore,

$$p_s = n\tau(1-\tau)^{(n-1)} \tag{11}$$

Moreover, to find the value of p_f in a time slot at least one n still transmit this yields as [44]

$$p_f = 1-(1-\tau)^n - 1 \tag{12}$$

Equations 5 and 6 represent a nonlinear system in the two unknowns τ and p_s that solved using Gregory-Newton Forward Difference Approach [45].

Consequently, it can use a similar approach to build the Markov chain model for duty-cycle MAC protocol of a saturated node to obtain the relationship between p_s and p_f because of low duty-cycle MAC protocols used the same factors like IEEE802.11 protocols to quantify the QoS parameters. Expect that there is extra delay in low duty-cycle MAC protocol which is caused by the sleep period of each node [46].

4.2 Media access rules of X-MAC

The hidden problem considers the first MAC problem that should be solved to investigate the network performance and to provide resource reservation and fulfill QoS requirements. Suppose that the transmission in sensor networks begins from node A that transmits data packets to node B as depicted in Fig. 5. Then, the propagation model between nodes A and B is given as

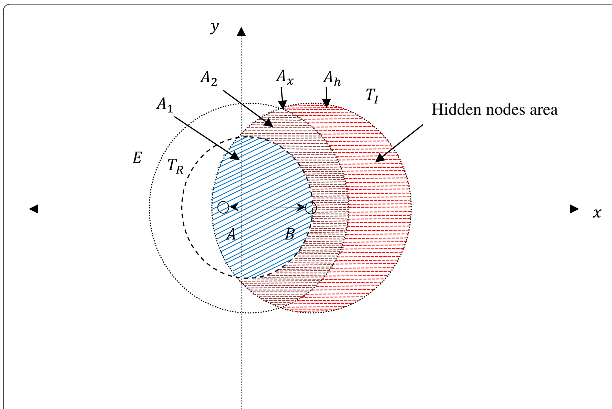

Fig. 5 Transmission, reception, and interference ranges

$$P_{\text{rx}}(B) = \frac{P_{\text{tx}}(A)}{\alpha d(A,B)^{\beta}}. \tag{13}$$

Therefore, the set of sensor nodes that are able to detect the transmission of node A is denoted as $N_{\text{tx}}(A)$ and defined as

$$N_{\text{tx}}(A) = \{x | d(x,A) \le R\}, \tag{14}$$

where R is the transmission range defined as

$$R = \sqrt[\beta]{\frac{P_{\text{tx}}(A)}{\alpha T_R}} \tag{15}$$

where the sensor nodes are distributed inside the dotted circle, the set of nodes N_{rx} that is distributed outside E transmission range is defined as $E = \sqrt[\beta]{\frac{P_{\text{tx}}(A)}{\alpha Sen}}$ cannot detect the transmission of node A [38]. This set is delimited by the shaded area and is calculated using the geometry equations as [1].

$$A_H(T_R) = \pi T_I^2 - 2T_I^2\left[\arccos\left(\frac{T_R}{2T_I}\right) - \frac{T_R}{2T_I}\sqrt{1-\left(\frac{T_R}{2T_I}\right)^2}\right] \tag{16}$$

Assume that $A_x(T_R)$ be the common shaded area that illustrates the locations at which possible hidden terminals reside. These circles of radius of E and T_I intersect at two points $\left(u, -\sqrt{E^2-u^2}\right)$ and $\left(u, \sqrt{E^2-u^2}\right)$ where $u = \frac{E^2+T_R^2-T_I^2}{2T_R}$. Therefore,

$$A_x(T_R) = [A_1(T_R) + A_2(T_R)], \tag{17}$$

where

$$A_1(T_R) = \int_{-T_I+T_R}^{u} \sqrt{T_I^2 - x^2}dx = T_I^2\left[\frac{\pi - a_2}{2} + \frac{\sin 2a_2}{4}\right], \tag{18}$$

$$A_2(T_R) = \int_{u}^{E} \sqrt{E^2 - x^2}dx = E^2\left[\frac{a_3}{2} + \frac{\sin 2a_3}{4}\right], \tag{19}$$

where $a_2 = \arccos\frac{u-T_R}{I_R}$ and $a_3 = \arccos\frac{u}{E}$. The average value of the hidden nodes are calculated as [47]

$$A_h(T_R) = \left[\pi I_R^2 - A_x(T_R)\right], \tag{20}$$

Hidden sensor nodes distributed inside the shaded area that illustrates the locations at which possible hidden terminals reside may limit the performance of contention-based MAC protocols. Because of their transmission results in collisions, the proposed model quantified the problem by deriving the probability of collision for avoiding this limitation.

The axioms of probability used to estimate the collision probability are performed by evaluating the dimensions of probabilistic of combination of events that might occur within A_x and A_h areas. Therefore, the derivation of collision probability depends on two rules: the addition rule which deals with the probability of union of more events; and the multiplication rule which deals with the probability of intersection of two events.

Suppose that E_x be an event which collision occurs by one or more nodes within A_x area, and E_h be an event which collision occurs by one or more nodes within A_h area. Then, the collision probability p_f is calculated as [1]

$$p_f = p_{E_x} + p_{E_h} - p_{E_x} p_{E_h}, \tag{21}$$

where p_{E_x} is the probability of the event E_x which is given as [1]

$$\begin{aligned} p_{E_x} =& Pr\{\text{two or more two awake sensor nodes in } A_x\} \\ &= \sum_{\jmath=2}^{\infty} \left(\sum_{\imath=\jmath}^{\infty} \binom{\imath}{\jmath} p_s^{\jmath} p(\imath, A_x) \right) \\ &= 1 - (1 + p_s \rho A_x) \exp^{-\rho A_x} \end{aligned} \tag{22}$$

where $p(\imath, A_x) = \frac{(\rho A_x)^{\imath}}{\imath!} \exp^{-\rho A_x}$ [1]. Likewise, p_{E_h} is define as the probability of the event E_h that can be obtained as in [1] by

$$\begin{aligned} p_{E_h} &= Pr\{\text{only one awake sensor node within } A_x\} \\ &= Pr\{\text{two or more two awake sensor nodes in } A_h\} \\ &= p_s \rho A_x \left(1 - \exp^{-(1-p_s)\rho A_x}\right) \\ &\left(1 - \exp^{-\rho A_h (1-(1-p_s))}\right) \exp^{-p_s \rho A_x} \end{aligned} \tag{23}$$

5 QoS parameter analysis of X-MAC protocol

QoS parameters expressed in terms of energy consumption, delay, and throughput can be calculated within a cycle time, since X-MAC works in duty-cycled fashion. Therefore, an active period of a wake-up node is defined in cycle time as T_{awake} time units. During this active period, the preamble packets data packet has size S, and an ACK message are assumed as $T_{\text{pre}}, T_{\text{Data}}$, and T_{ACK} time slot units to transmit, hence, Markov model has a unique stationary distribution $\pi = \pi_0, \ldots, \pi_M$ [29].

Usually, X-MAC uses a fixed-preamble size carrying the address of the sink to transmit the data packet. Suppose that a sensor network is fully connected with n nodes, and then each node wakes up periodically for successful transmission of a data packet with probability $(1 - \pi_0)p_s$ which takes time on average $\frac{T}{2} + T_{\text{Data}}$. Each node uses $\frac{T}{2}$ periodically to send preamble packets and then a node starts to listen to the ACK messages between two successive preamble packets, whereas T_{Data} is used periodically to successfully transmit a data packet with specific probability. Hence, the average time it takes to send preamble packets is $\frac{T}{2}\left(\frac{T_{\text{pre}}}{T_{\text{pre}}+T_{\text{ACK}}}\right)$. The average time a node takes to listen to the media is $\frac{T}{2}\left(\frac{T_{\text{ACK}}}{T_{\text{pre}}+T_{\text{ACK}}}\right)$. Finally, the amount of energy that is consumed in this case is calculated as [18]

$$\begin{aligned} \text{Energy}_1 =& (1-\pi_0) p_s \tau \left(\frac{T}{2}\left(\frac{T_{\text{pre}}}{T_{\text{pre}} + T_{\text{ACK}}}\right)\right) P_{\text{TX}} \\ &+ \frac{T}{2}\left(\frac{T_{\text{ACK}}}{T_{\text{pre}} + T_{\text{ACK}}}\right) P_{\text{RX}} + T_{\text{Data}} P_{\text{RX}} \end{aligned} \tag{24}$$

In similar case, a node wakes up periodically to unsuccessful transmission of a data packet with probability $(1 - \pi_0)p_f$ that implies other node synchronizes to send preamble packets. However, in this case, there is no preamble packets that may be received correctly because of collision, and then the node continues sending preamble packets with average time $T\left(\frac{T_{\text{pre}}}{T_{\text{pre}}+T_{\text{ACK}}}\right)$, and the average time of listen to media between two successive preambles is $T\left(\frac{T_{\text{ACK}}}{T_{\text{pre}}+T_{\text{ACK}}}\right)$. The amount of energy consumed in this case is [18]

$$\begin{aligned} &\text{Energy}_2 = \\ &(1-\pi_0) p_f \tau \\ &\left\{\left(T\left(\frac{T_{\text{pre}} + T_{\text{ACK}}}{2P_{\text{RX}} + T_{\text{pre}}P_{\text{RX}} + T_{\text{ACK}}P_{\text{TX}} + T_{\text{Data}}P_{\text{RX}}}\right)\right)\right\} \end{aligned} \tag{25}$$

Suppose that the node has received complete preamble packets, then it sends back T_{ACK} message to receive the data packet. However, any intermediate nodes may wake up to send a preamble packet or listen to receive T_{ACK} message from the sink. As a result, the time on average of the receiving node is $\frac{T_{\text{pre}}+T_{\text{ACK}}}{2}$. Therefore, the amount of energy consumed is

$$\begin{aligned} \text{Energy}_3 = (1-\pi_0) p_f \tau \left(T\left(\frac{T_{\text{pre}}}{T_{\text{pre}} + T_{\text{ACK}}}\right)\right) \\ P_{TX} + T\left(\frac{T_{\text{ACK}}}{T_{\text{pre}} + T_{\text{ACK}}}\right) P_{\text{RX}} \end{aligned} \tag{26}$$

$\frac{T_{\text{pre}}+T_{ACK}}{2+T_{pre}}$ because it cannot detect the collision until it hears the next colliding preamble packets. Hence, the amount of energy consumed is

$$\begin{aligned} \text{Energy}_4 = (1-\pi_0) p_f \tau \\ \left(\frac{\left(T_{\text{pre}} + T_{\text{ACK}}\right)}{2P_{\text{RX}} + T_{\text{pre}}P_{\text{RX}}}\right) \end{aligned} \tag{27}$$

Totally, the energy consumption per hop per second can be obtained as

$$\text{Energy} = \sum_{i=1}^{4} E_\iota \tag{28}$$

The analysis of the delay of data packet depends on the probability of successful transmission p_s for each node that wins the contention and the steady state of the Markov model π_0 during the cycle. Therefore, a node starts to send contends for the media during the cycle until win the contention with probability p_s and the probability $1 - p_s$ to lose the contention. Hence, the delay is given along cycle length T.

$$\text{Delay} = T \sum_{\iota=1}^{\infty} (\iota + 1) p_s (1 - p_s)^\iota \tag{29}$$

The derivation of the probability of successful transmission and collision in X-MAC protocol depends on the status of the queue and the channel. This means that a node have *empty*/$\overline{\textit{empty}}$ queue according to the steady state free/busy of the proposed Markov chain model. Further, the status of channel is free/busy according to detection of collision occurring by event. Suppose that A defines an event that occurs by one or more two node winners in the contention within the area A_x. And B is defined as an event that occurs by two or multiple node winners in the contention with area A_h. Then [9],

$$p_s = P_r(A, \text{free}|\text{empty}) = P_r(A|\text{free}, \overline{\text{empty}}) P_r(\text{free}|\overline{\text{empty}}) \tag{30}$$

$$p_f = P_r(B, \text{free}|\text{empty}) = P_r(B|\text{free}, \overline{\text{empty}}) P_r(\text{free}|\overline{\text{empty}}) \tag{31}$$

To solve for $P_r(A, \text{free}|\text{empty})$ and $P_r(B, \text{free}|\text{empty})$, assume that a node has an empty queue and directly wakes up and detects the event and transmit a data packet for its neighbors. At the same time, other nodes wake up but do not have any data packet for transmission. Therefore,

$$P_r(A|\text{free}, \overline{\text{empty}}) = \sum_{t=1}^{T} \frac{1}{T} \left(\sum_{\iota=1}^{N_c-1} \binom{N_c - 1}{i} \frac{1}{T}^{\iota} \pi_0^i \left(\frac{T-1}{T} \right)^{N_c-1-\iota} \right) \tag{32}$$

Similarly, when one other node wakes up and has data packet for transmission then a collision occurs, therefore, the collision probability is

$$P_r(B|\text{free}, \overline{\text{empty}}) = \sum_{t=1}^{T} \frac{1}{T} \left(\sum_{\iota=1}^{N_c-1} \binom{N_c - 1}{\iota} \left(\frac{1}{T} \right)^{\iota} \left(\sum_{j=1}^{\iota} (1 - \pi_0)^j \pi_0^{\iota - j} \left(\frac{T-1}{T} \right)^{N_c-1-\iota} \right) \right) \tag{33}$$

$P_r(\text{free}|\text{empty})$ is defined as the probability of a free channel when a node wakes up and has data packet in its queue ready for transmission. As mentioned, each node in X-MAC protocol periodically wakes up and sends preamble packets and then a node starts to listen to channel; the channel have the same probability of being free or busy in every time slot [18]. Hence, when a node wakes up, no matter whether its queue is empty or not, the node sees the channel with the same probability of being free or busy. Therefore,

$$P_r(\text{free}) \approx P_r(\text{free}|\overline{\text{empty}}) \tag{34}$$

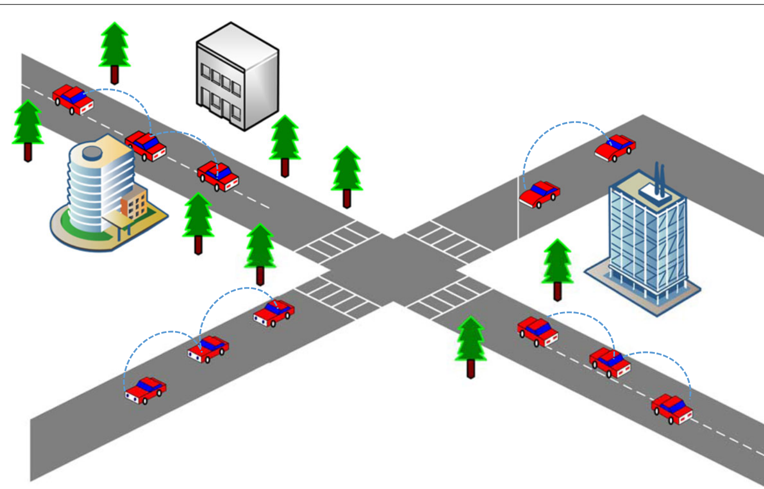

Fig. 6 Network topology to evaluate the X-MAC protocol

Table 2 Experiment parameters for X-MAC protocol

Parameter	Value
T	200 ms
t_{Data}	50 ms
t_{sync}	30 ms
t_{RTS}	15 ms
t_{CTS}	15 ms
t_{ACK}	5 ms
Topology structure	Square (50 $\times$ 50 m^2), sensor node distributed uniformly
Total number of sensor nodes	5, 12, 17 sensor nodes
Message payload	64 b
Node density	.002, .005, .007
Tx data rate	250 kbps
Transmission range	$18 - 29$ m
Propagation delay	1 μs
tx_{xp}	0.0525 W
rx_{xp}	0.0591 W
sp	0.0525 W

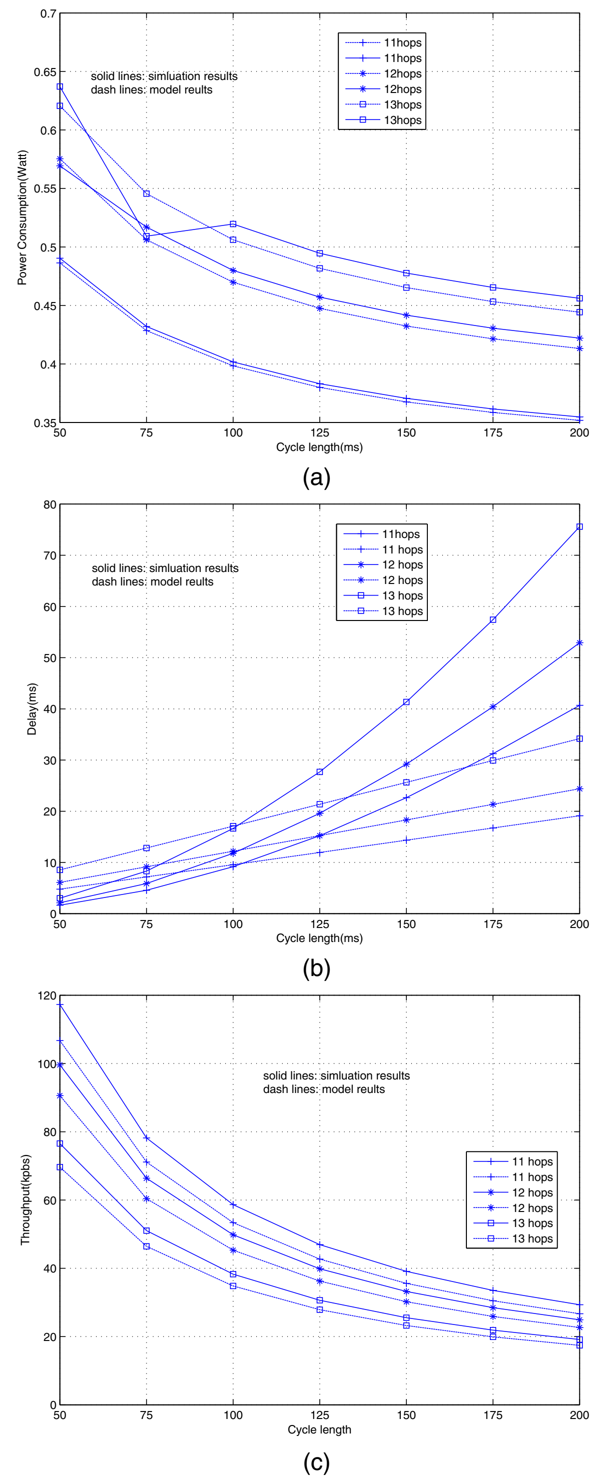

Fig. 7 X-MAC performance with varying cycle length. **a** Power consumption, (**b**) Delay, (**c**) Throughput

The probability of free channel is determined by two parameters: (a) the average length of the free channel; and (b) the average length of the busy channel. Therefore, the probability of free channel is expressed as

$$P_r(\text{free}) = \frac{C_{\text{free}}}{C_{\text{free}} + C_{\text{busy}}} \quad (35)$$

To calculate C_{free}, assume that the interval of time transmission ends, and the free channel begins, there are number of cycles *cycle* that could define the free channel until some nodes begin to transmit at t^{th} slot. Thus, the average length of free channel is $cycleT + t$, and the probability of transmission event is [18]

$$P_{\text{free}}(\text{cycle}, t) = \pi^{N_c\text{cycle}} \Sigma_{\iota=0}^{N_c-1} \Sigma_{j=1}^{N_c-\iota} \Sigma_{k=1}^{j} \binom{N_c}{\iota} \left(\frac{t}{T}\right)^{\iota} \pi_0^{\iota} \binom{N_c-\iota}{j} \left(\frac{1}{T}\right)^{j} \binom{j}{k} (1-\pi_0)^k \pi^{j-k} \left(\frac{T-t-1}{T}\right)^{N_c-\iota-j} \quad (36)$$

Therefore, the average length of free channel can be obtained as [18]

$$C_{\text{free}} = \sum_{\text{cycle}=0}^{\infty} \sum_{t=0}^{T-1} (cycleT + t) * P_{\text{free}}(cycle, t) \quad (37)$$

The successful transmission probability P_{suc} could be similar as the obtained probability of collision P_{col} as long as the channel is free for *cycle* cycles and t slots.

Therefore, both successful transmission and collision are calculated as [18]

$$P_{\text{suc}}(cycle,t) = \pi_0^{N_c} \Sigma_{\iota=0}^{N_c-1} \Sigma_{J=1}^{N_c-\iota} \binom{N_c}{\iota} \left(\frac{t}{T}\right)^{\iota} \pi_0^{\iota} \binom{N_c-\iota}{J} \left(\frac{1}{T}\right)^{J} \binom{J}{1} (1-\pi_0)\pi^{J-1} \left(\frac{T-t-1}{T}\right)^{N_c-\iota-\iota} \quad (38)$$

$$P_{\text{col}}(cycle,t) = \pi_0^{N_c} \Sigma_{\iota=0}^{N_c-2} \Sigma_{J=2}^{N_c-\iota} \Sigma_{k=2}^{J} \binom{N_c}{\iota} \left(\frac{t}{T}\right)^{\iota} \pi_0^{\iota} \binom{N_c-\iota}{J} \left(\frac{J}{k}\right)^{J} (1-\pi_0)^k \pi_0^{J-k} \left(\frac{T-t-1}{T}\right)^{N_c-\iota-J} \quad (39)$$

The average length of a busy channel can be calculated according to the successful transmission data packet which takes on average time $\frac{T}{2} + T_{\text{Data}} + P_{\text{suc}}$. Therefore,

$$C_{\text{busy}} = \sum_{\text{cycle}=0}^{\infty} \sum_{t=0}^{T-1} \left(\left(\frac{T}{2} + T_{\text{Data}}\right) P_{\text{suc}}(\text{cycle},t) + TP_{\text{busy}}(\text{cycle},t) \right) \quad (40)$$

Substituting Eqs. 38 and 35 into 33, then $P_r(\text{free})$ is obtained. Plugging 30 and 32 into 28, and then plugging 31 and 32 into 29, the successful transmission probability for each node p_s the probability of collision p_f are obtained. Therefore, the throughput per second per hop of X-MAC protocol can be calculated as

$$\text{Throughput} = N_c(1-\pi_0)p_s \frac{S}{(T\tau)} \quad (41)$$

6 Simulation results

Consider that a vehicle is equipped with wireless devices; therefore, they can communicate with each other. However, the primary application is to let vehicles exchange about their current context in order to detect abnormal events in an urban environment. The network topology is shown in Fig. 6; our proposed model provides detailed analysis for the performance of a synchronized X-MAC protocol under the impact of the hidden problem as well as under unicast traffic for various network configuration, conditions, and other assumptions for specific scenarios. The analytical correctness of the proposed model was validated through implementation using MATLAB [48].

In all the simulations to be presented in the paper, the network set-up is a fully connected with varying number of connected nodes, i.e., vehicles. The transmission range of each vehicle is 18 m, and the cycle length of time period is 50 s. For each set of simulation, energy consumption, delay, and throughput are investigated under varying network parameters of the vehicle. The values of the network parameters used are summarized in Table 2. These parameters are set to comply with the X-MAC protocol specifications. All vehicles are distributed rating using a two-dimensional Poisson distribution within an area of $50 \times 50\, m^2$.

Figure 7 shows the performance of X-MAC protocol for multihop communication fashion under varying cycle length T from 50 to 200 ms as shown in Fig. 8. Figure 9 shows the performance of X-MAC protocol under varying vehicle densities in the network and transmission range of each vehicle varying from 18 to 29 m as shown in Fig. 10. From these results, it can be seen that the analytical results of the proposed model match the simulation results.

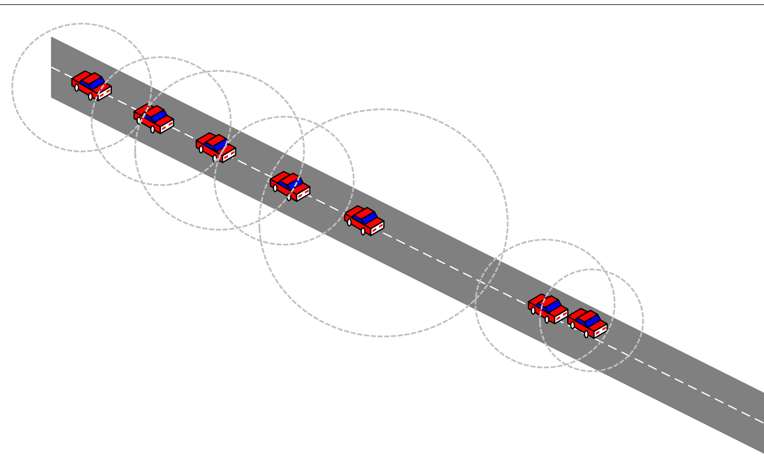

Fig. 8 First experiment to evaluate the X-MAC protocol

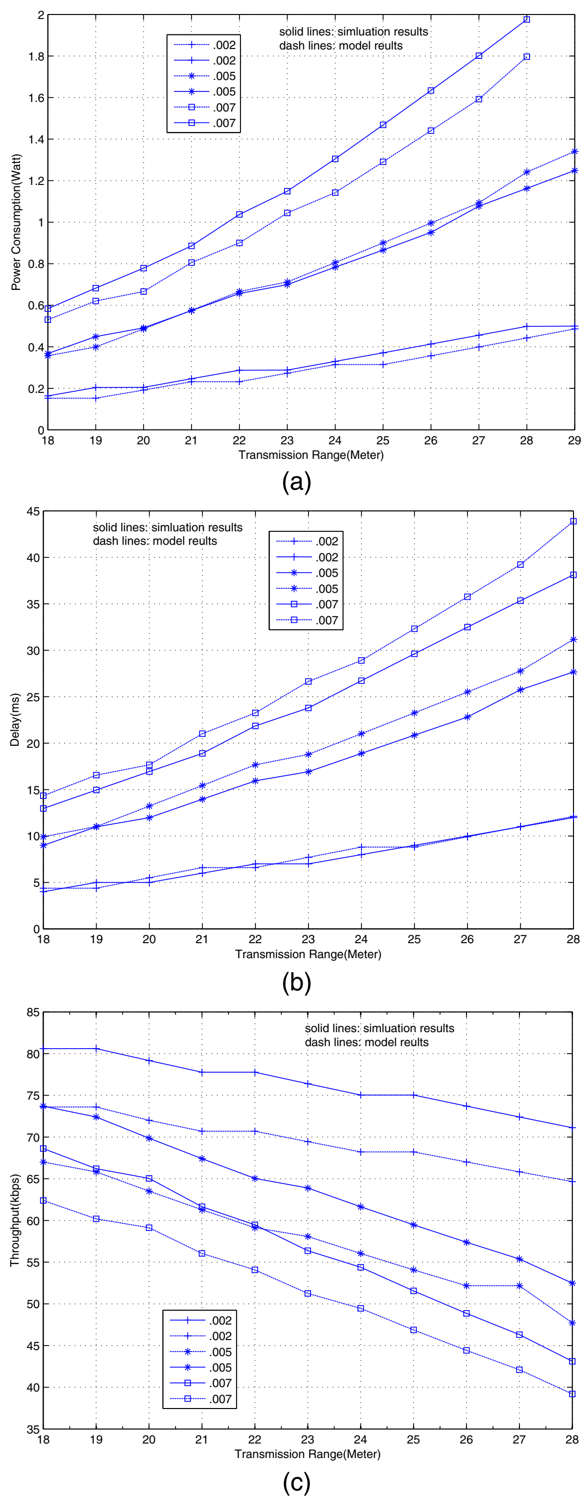

Fig. 9 X-MAC performance with varying transmission range. **a** Power consumption, (**b**) Delay, (**c**) Throughput

6.1 Varying the cycle length

In this experiment, we vary the cycle length, Fig. 7a shows the power consumption of the X-MAC protocol obtained from simulations and from our power consumption analysis using the Markov model. Our analytical results match the simulation results with percentage difference or max difference in power consumption. The power consumption decreases as the length of cycle period increases which means that whenever the cycle length increases, the unsuccessful data transmission increases due to increase in the rate of collision probability. Consequently, as the cycle length increases and as the number of vehicles increases, the power consumed in data transmission increases, and the active period in each cycle is fixed. Therefore, all vehicles in the network expect the source vehicle and the sink node in either successful transmission or unsuccessful transmission to go to the sleep state as long as the cycle length increases. Thus, the power saving in this longer sleep period is more than in longer transmission period, the power consumption of X-MAC protocol decreases as the cycle length increases.

Figure 7b shows that the average delay of the X-MAC protocol increases as the length of cycle period increases. Usually, before the X-MAC protocol saturates and the cycle length starts from small value with a few vehicles in the network. X-MAC protocol can deliver all the incoming data packets as soon as they arrive in the network, hence, the delay is nearly zero. Once X-MAC protocol saturates and the cycle length increases, both the contention and queue delay increases proportional to the increases of the cycle length and the number of nodes. Since the X-MAC protocol can no longer deliver all the incoming data packets, the queue at each vehicle overflows and data packets are dropped.

Figure 7c reveals that the average throughput of the X-MAC protocol decreases as the cycle length increases and as the number of vehicles in the network increases. This means that before X-MAC saturates, the amount of incoming data packet delivered remains in the queue and slightly decreases when X-MAC protocol saturates and as the number of vehicles in network increases further. As the X-MAC protocol can no longer deliver all the incoming data packets because of the increasing collisions at the following specified period.

6.2 Varying the number of nodes

In this experiment, we vary the number of vehicles. Figure 9 shows that the power consumption of X-MAC protocol increases under varying vehicle densities in the network and transmission range of each vehicle in the network as seen in Fig. 10. Whenever the transmission range increases, the unsuccessful data transmission increases since the rate of collision probability increases and hence more power is consumed. Consequently, as the transmission range increases and as the number of vehicles increases, the power consumed in data transmission increases, as the active period in each cycle

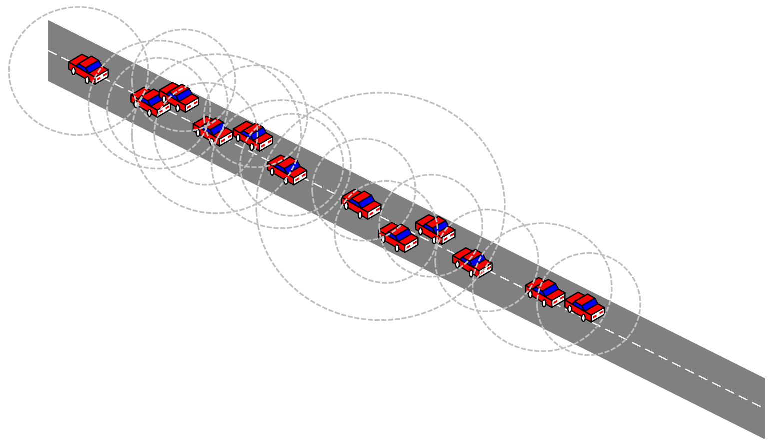

Fig. 10 Second experiment to evaluate the X-MAC protocol

is fixed. Therefore, all vehicles in the network expect the main vehicle source and the main sink node in either successful transmission or unsuccessful transmission wake-up as longer as the cycle length increases. Thus, power savings in this longer sleep period became more than in longer transmission period, the power consumption of X-MAC protocol decreases as the cycle length increases.

Figure 9b shows the delay of the X-MAC protocol. Before X-MAC saturates, the delay slowly increases with lower node density and with fewer variation in the transmission range vehicle in cycle. Moreover, as the number of vehicles increases, a vehicle tends to have a higher probability of successful transmission leading to saturation state. Therefore, the delay dramatically increases as X-MAC saturates because of the increases in the rate of collision probability in a cycle. This means that the more vehicles in the network leads to decreasing the probability of successful transmission of packets when X-MAC saturates. Hence, according to the main parts of X-MAC protocol data packets delay (the queue delay and contention delay) this increase is obvious when the number of vehicles and the transmission range increase.

Figure 9c shows the throughput of X-MAC protocol. Before X-MAC saturates, the amount of incoming data packet in cycle remains, the node can deliver all incoming data packets in cycle. Once the transmission range of vehicle in a cycle increases, the throughput decreases as well as the vehicle density increases. This means that X-MAC can no longer deliver all incoming data packets, because of increasing the transmission range leading a vehicle tends to have higher probability of successful packet transmission leading to saturation state. Therefore, the throughput shrinks dramatically because of the increase in the probability of collision.

6.3 Discussion

The proposed Markov model for asynchronous duty-cycled MAC protocols has been applied in X-MAC protocol to optimize some protocol parameters to achieve desirable performance. Conceptually, X-MAC is considered as higher efficient protocol than synchronized S-MAC protocol because of the avoidance synchronization overheads. Therefore, asynchronous X-MAC can achieve more desirable performance than synchronized S-MAC for the delay and throughput [49]. But this does not mean that asynchronous X-MAC does not suffer from hidden terminals especially when varying the vehicles and density. As the vehicles and density increases, more than one vehicle wake up and begin to send their preambles simultaneously. Therefore, other vehicles cannot determine the information in preambles and collisions occur. Consequently, and based on the assumption used in Markov model in synchronous MAC protocol, our proposed model uses two different values of probabilities for transmission and collision, p_s and p_f, respectively, to handle the hidden terminal problem and to estimate the communication links performance. Finally, we should distinguish between the effect of asymmetric and symmetric links in order to provide the adequate functionality to routing protocols. Asymmetric links are caused by several factors like node mobility, heterogeneous radio technologies, and irregularities in radio ranges. Although it is difficult to achieve high network connectivity, high data rate transmission, and low latencies, but according to our observations, it is expected that asymmetric links will be more common in the future VSNs. Actually, the hidden terminal problem will be more complicated with the existence of asymmetric links, where the receiver and the sender do not share the channel feedback and hidden nodes may interfere with the on going transmissions [50]. Furthermore, because of the feedback from the receiver in

RTS/CTS, exchanged messages may have to pass through several relay nodes before being delivered to all others nodes. However, MAC protocols might need to exploit asymmetric links to solve the hidden terminal problem while maintaining the lowest cost. In fact the network utilization and cost are weights derived and constrained by the network resource management (NRM) approach, where some routing or MAC protocols based on QoS parameters such as (power consumption, throughput, and latency) are application-dependent and imposed by the node specification. Therefore, to optimize these parameters in order to achieve the desirable benefits and network performance, the NRM approach shall be chosen based on the desire QoS parameters. As a result, the inclusion of asymmetric links in the MAC protocol design can further improve the network performance.

7 Conclusions

In this paper, the QoS parameters of X-MAC are modeled and analyzed using Markov chain model. Our model presents analytical results which have been validated by simulation results for the selected QoS parameters under various network conditions and traffic loads. It provides sufficient information about the links between the vehicles to determine the optimal path and to select the intermediate nodes for packet routing from source to distention. Our future work will focus on analyzing the QoS parameters for synchronized protocols and extending the model to multihop networks.

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Authors' contributions
MZH and FA-T conceived the idea and wrote the paper. MZH performed the experiments and analyzed the data. FA-T gave valuable suggestions on the motivation of this work and assisted in revising and proofreading the paper. Both authors read and approved the final manuscript.

Competing interests
Both authors declare that they have no competing interests.

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