Energy and delay optimized contention for wireless sensor networks

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Abstract

In wireless sensor network (WSN) studies, the main objective is minimizing the energy consumption so that the lifetime is maximized under the limited battery capacity constraints. Additionally, in most event-driven WSN applications, the end-to-end delay, and hence, the medium access delay should be minimized. Majority of the WSN MAC protocols are contention-based wherein contention window size setting involves an important trade-off between the collision probability and idle listening durations in contentions where both are aimed to be lowered for efficient network operation. In this paper, the energy optimizing and the delay optimizing contention window sizes are derived as a function of the number of contending nodes. For this purpose, we present separate analyses for the contention delay and for the energy consumed which are verified with detailed simulations. In order to obtain close to optimal performance values in a distributed manner, we propose a method for estimating the number of contending nodes since the individual wireless sensor nodes do not have this information readily. Simulations of an event-driven WSN application verify that the proposed method successfully improve both delay and energy efficiency of the contention-based medium access. The end-to-end network performance is also investigated by employing a geographical routing protocol. Results show that using the heuristic method proposed that use the optimum contention window size analyses presented, the overall network performance can be improved without incurring any overhead to the system.

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1. Introduction

The limited battery capacities of the sensor nodes require energy-efficient operation of the wireless sensor networks (WSNs). As a result, researchers concentrated on WSN-specific protocols that reduce the redundant communication to preserve power that either obey the layered approach or exploit the cross-layer interactions for efficiency. Accordingly, medium access scheme should also be optimized considering the energy efficiency. WSN designers prefer contention-based medium access schemes such as those used in Xbow sensor nodes [1]. The reason for that is unlike TDMA-based access schemes, the contention-based protocols do not need precise time synchronization and do not need extra circuitry as required by FDMA-based systems. Moreover, the computational complexity added by the CDMA-based schemes results in higher energy consumptions.

Contention-based protocols commonly perform slotted medium access via contention windows (CWs) [2–5] that are composed of a specific number of contention slots. Each contending node starts its CW at the beginning of contention periods where they select a slot in the contention window in a uniformly random manner. Each contending node, then, listens to the medium till its slot time arrives or till it receives the transmission of another node before its slot time. As a result, the contending node(s) that selects the slot with the lowest index acquires the medium. All the other nodes receive this transmission and perform a back-off till the next contention window.

Idle listening and collisions are two main types of energy waste for sensor nodes that occur during the medium...
access. Idle listening occurs if a destination node listens to the medium when there is no transmission whereas a collision occurs if a destination node receives multiple transmissions at the same time. An efficient communication protocol should reduce both kinds of energy waste. In contention-based medium access, all contending nodes do carrier sensing till the first occupied slot which results in idle listening. On the other hand, if the first occupied slot is actually selected by two or more nodes, packet transmissions of these nodes start at the same slot which results in a collision.\(^1\) A contention scenario that results in a collision is illustrated in Fig. 1. Four sensor nodes contend for the medium and in the first contention window, the first occupied slot is actually occupied by the nodes 2 and 3. Both nodes start their packet transmissions at their slot time resulting in a collision. The transmitting nodes detect the collision by observing no reply from the destination nodes. After not receiving any reply for a collision timeout duration, \(t_c\), all the contending nodes start a new contention window for the retry. The time passed till the start of the successful contention is denoted as the collision and the retrial duration after which the successful contention occurs in which carrier sensing is done till the first occupied slot of the successful slot assignment. The total contention duration is dependent on the collision and the retrial duration and the carrier sensing duration in the successful slot assignment.

In contention-based schemes, the CW size creates a trade-off between the two types of energy waste, since a larger CW results in longer expected idle listening because of the carrier sensing and a smaller CW increases the probability of collisions. To set the CW size carefully is therefore very crucial for energy-efficient operation. Although there exist studies proposing CW adjustment methods for IEEE 802.11, these studies consider the binary exponential backoff (BEB) which is not preferred in WSN due to its exponential size increase [4,7–10]. In addition, the common objectives of these studies are improving the fairness (e.g. [3]) and the throughput (e.g. [11]) which are not the main objectives of WSNs. A distinctive CW size setting method is necessary for WSNs which is not yet studied in detail. As a numerical example, S-MAC [4] defines a fixed size of 63 contention slots in its ns-2 [12] code where one slot time is set to be the time to transmit 20 bits. Consequently, if a node contends for the medium alone, the expected carrier sense time is \(63/2 = 31.5\) slots which corresponds to the transmission duration of 630 bits. However, the size of one data packet is generally small in WSN applications, for instance 400 bits in S-MAC defaults, which results in more time and energy consumption for contentions compared to the actual data transmission. As a result, the contention-based communication is not efficient when the contention window size, that actually requires an engineering optimization, is set independently from the network properties.

The energy consumption caused by the contention-based medium access is affected significantly by the CW size. In this paper, we show that the energy consumed for contentions can be reduced significantly by setting the contention window size to its energy optimizing value. We derive an analytical formula for the energy consumption as a function of the contention window size and the number of contending nodes. Another possible objective in WSNs is minimizing the latency, i.e., the delay between the event and the notification of the sink. This objective is especially crucial for time-critical applications such as intrusion detection and tactical systems. To decrease the latency observed, the contention delay, i.e., the time till the successful medium access has to be minimized. The contention delay is also formulated as a function of the contention window size and the number of contending nodes which is used to find the delay optimizing CW size.

Although the energy optimizing and the delay optimizing CW sizes can be found using the derived equations, the knowledge of the number of contention nodes used in the equations may not be readily available at individual sensors. In practice, each node should have a method to approximate that information for a distributed implementation. In this paper, we propose the Estimated Number of Contenders (ENC0) method for the event-driven WSNs based on the mean coverage degree idea [13]. We demonstrate that the ENCO method can give close results to the theoretical best medium access performance.

The end-to-end network performance is affected by the medium access settings. While the optimizations presented in this paper improve the medium access performance significantly, its effect on the overall network performance is also investigated for a WSN application. It is observed that by setting the CW size with the ENCO method that use the optimizations provided, the end-to-end network performance is also improved without bringing any overhead to the network.

The rest of the paper is organized as follows. A brief overview of the contention window size related studies

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\(^1\) For the sake of simplicity, we assume that when multiple contending nodes transmit at the same slot, collision occurs at the destination nodes. This assumption is reasonable in accordance with [6] that shows the interference ranges of the contending nodes include the transmission ranges of each other.
are presented in Section 2. The relation between the contention window size and the contention delay is investigated analytically in Section 3.1. The energy consumption for the resolution of all contending packets requires a separate analysis which is presented in Section 3.2. Then, the derived analytical formulas are verified with simulations in Section 4. The ENCO method is presented for a distributed implementation along with its efficacy in medium access in Section 5. The effect of the ENCO method on the end-to-end network performance is demonstrated with the simulations in Section 6. Finally, Section 7 concludes the paper.

2. Related work

Since the sensor nodes do not transmit and receive at the same time, a collision is recognized by the sender nodes with the lack of ACK or CTS reply depending on whether CSMA or CSMA/CA is implemented. In the case of collisions, IEEE 802.11 and IEEE 802.15.4 standards use binary exponential backoff (BEB) which requires doubling the CW size at each collision. However, since BEB results in exponential increase of window size on collisions and hence long carrier sense times [10,14], instead of the exponential backoff method, the uniform backoff method is preferred in WSNs as used in S-MAC [4], B-MAC [7], SCP-MAC [8], Z-MAC [9] and Sift [10]. The difference in the backoff method and the distinct objectives of WSNs such as the minimization of the energy consumption require a separate CW size analysis. The use of optimized CW sizes in a distributed environment is another crucial topic for WSNs which is also investigated in this paper.

The impact of the CW size on the medium access performance has been studied previously especially for IEEE 802.11 and IEEE 802.15.4 networks. Although these IEEE 802 protocols do not employ uniform backoff, it is still worthwhile to summarize the previous research on CW size setting for these protocols. Wang et al. show that although the IEEE 802.11 DCF with RTS/CTS is not affected by the initial CW size significantly, the effect is considerable without RTS/CTS [15]. To decrease the probability of collisions under congested traffic in IEEE 802.11 networks, Ksentini et al. propose a new CW size adjustment method which defines a backoff lower bound in combination with doubling the CW size [16] that is referred as the backoff range.

A method to tune the CW size by observing the network traffic is proposed in [17]. The proposed algorithm computes an estimate of the collision cost and an estimate of the number of active stations assuming that all contending stations continuously have packets ready for transmission. These estimates are obtained by observing the three events that occur on the channel: idle slots, collisions, and successful transmissions. Similarly, the algorithm proposed in [18] aims to approximate the number of contending nodes from the number of idle slots observed before packet transmissions and dynamically adjust the CW size till a designated optimum number of consecutive idle slots are reached. However, these methods require a closed system with continuous traffic load to converge. Although, Xia et al. defines a feedback control system in [19] that makes the former proposed method adaptive to changes in the number of contending nodes, it still requires stable and continuous traffic loads to approximate the number of nodes successfully. Ma et al. propose that AP (Access Point) counts the number of contending nodes and judges whether the CW parameters should be changed or not for coordinated medium access [20]. In case a change is needed for performance issues, the AP announces it to all of its nodes. Since in contention-based WSN, the number of contending nodes is dynamic and cannot be known by individual sensors in advance, an approximation method is needed to benefit from the optimized CW size information. The effect of different network conditions related to the CW adjustment method is also investigated. For instance, Jin et al. investigate the stability of IEEE 802.11 where selfish users exist in the network that dynamically change their CW sizes overriding the standard window size update procedure [21].

IEEE 802.11e introduces the enhanced distributed coordination function (EDCF) which defines different CW size settings for different traffic classes to achieve QoS requirements. Several techniques have been proposed to enhance the performance of EDCF such as the Sliding Contention Window method [22] which adjusts the backoff ranges of the traffic classes according to the QoS requirements and dynamic network behavior. In [23], another adaptive technique is proposed for IEEE 802.11e which takes the congestion level of the network into account, by considering the previous CW size values, for the decision of resetting the CW size.

The unslotted CSMA-CA in IEEE 802.15.4 for the nonbeacon-enabled mode has no power saving mechanism, hence the slotted version for the beacon-enabled mode is preferred for energy-efficient network operation [5]. Pang et al. propose a memorized backoff scheme to dynamically adjust the CW size based on the traffic load [24]. A retransmission algorithm that uses a Synchronized, Shared Contention Window (SSCW) is proposed in [25] where an analytical approximation is presented for the optimization of the CW size as a function of the probability of collision in the contentions.

For WSNs, a two level contention window is proposed in SCP-MAC to improve the contention performance [8]. Similarly in Z-MAC [9], two different CW sizes are proposed for prioritization. However, since the CW sizes in both methods are constant, the size settings are still critical. Although the uniformly random slot selection is generally used in contention-based schemes, alternative slot selection distributions are also proposed. Tay et al. proposed a slot selection distribution which minimizes the collision probability [26] and Sift protocol employs a practical variant of this distribution [10]. Nevertheless, there is still a possibility of collision and the total contention time or the consumed energy must be optimized considering the probability of collisions. A default CW size of 63 is defined in ns-2 code of S-MAC where the CW size is advised to be in the format of $2^n – 1$ most likely for computational

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2 The non-exponential backoff method that does not alter the CW size is referred as uniform backoff in this paper.
3. Impact of contention window size on the crucial WSN objectives

The two crucial objective functions in WSN research are the minimization of the delay and the minimization of the energy consumption. In contention-based medium access, these metrics are shaped by the contention delay and the energy consumed during the contentions, respectively. In this section, we investigate the effect of CW size on both metrics by analyzing them as functions of the CW size and the number of contending nodes.

3.1. Contention delay

The expected contention delay is defined as the expected duration between the beginning of the contention till a successful medium access and denoted as $\Omega$. As shown in Fig. 1, it can be decomposed into two phases: (i) the expected time spent for collisions and retrials till the beginning of the collisionless slot selection, $\Lambda$, and (ii) the expected carrier sense duration within this successful contention from the beginning of the contention window till the first occupied slot, $\Gamma$. We will derive the equations of both components in terms of the contention window size, $W$ and the number of contending nodes, $N$. At each contention, $N$ nodes select a slot independently and uniformly randomly from the slots $1 \cdots W$.

Let the random variable $\Psi$ represent the first occupied slot number either the slot selection results in collision or not. The probability that the first occupied slot is $\psi$, $Pr[\Psi = \psi]$ is defined as

$$Pr[\Psi = \psi] = Pr[(s_i \geq \psi), \forall i \in \{1, \ldots, N\} \land (s_i = \psi), \exists i \in \{1, \ldots, N\}], \tag{1}$$

where $s_i$ represents the slot chosen by node $i$. Consequently,

$$Pr[\Psi = \psi] = \frac{(W - \psi + 1)^N - (W - \psi)^N}{W^N}. \tag{2}$$

Firstly, we analyze the expected carrier sense duration for a collisionless slot selection, $\Gamma$. If the first occupied slot is $\psi$ then the carrier sense duration of that contention will be $(\psi - 1)t_c$ where $t_c$ is one slot duration. Then,

$$\Gamma = \sum_{\psi=1}^{W} Pr[\Psi = \psi | \mathcal{T} = \text{success}] (\psi - 1)t_c, \tag{3}$$

where random variable $\mathcal{T}$ indicates whether the slot selection is successful, i.e., collisionless. However, by the definition of the conditional probability,

$$Pr[\Psi = \psi | \mathcal{T} = \text{success}] = \frac{Pr[\Psi = \psi, \mathcal{T} = \text{success}]}{Pr[\mathcal{T} = \text{success}]} \tag{4}$$

Note that $Pr[\Psi = \psi, \mathcal{T} = \text{success}]$ represents the probability that $\psi$ is the first occupied slot and it is selected by only one node. There are $W^0$ different slot assignment possibilities among which the following assignment results in collisionless transmission: $\psi$ is chosen by any of $N$ nodes and the slots $\psi + 1$ to $W$, i.e., $W - \psi$ slots, are chosen randomly by $N - 1$ nodes. As a result,

$$Pr[\Psi = \psi, \mathcal{T} = \text{success}] = \frac{N(W-\psi)^{N-1}}{W^N}. \tag{5}$$

Hence,

$$\Gamma = \sum_{\psi=1}^{W} Pr[\Psi = \psi | \mathcal{T} = \text{success}] (W-\psi)^{N-1} = \frac{W^{N-1} \beta}{\lambda^N}. \tag{6}$$

The retrials will continue until a collisionless slot selection occurs. Therefore, the expected time spent for collisions and retrials equals the expected number of retrials, $\beta$, times the expected time elapsed in one retrial, $\lambda$, in other words,

$$\Lambda = \beta \lambda. \tag{7}$$

Since each contention is an independent and random event, contentions can be represented with a Bernoulli trial with success and fail probabilities of $\zeta$ and $\bar{\zeta}$ which corresponds to the contentions with no collision and with collision, respectively. The expected number of collisions and the resulting retrials are then found to be

$$\beta = \frac{1}{\beta} - 1, \tag{8}$$

since $\frac{1}{\beta}$ gives the expected number of trials till success for this Bernoulli trial. Therefore,

$$\Lambda = \lambda \left( \frac{1}{\beta} - 1 \right). \tag{9}$$

Assume that $t_c$ is the duration passed for the packet transmission, for the collision to be understood and the new contention begins which is referred as the collision timeout in this paper. Then,

$$\lambda = \left( \sum_{\psi=1}^{W} Pr[\Psi = \psi | \mathcal{T} = \text{fail}] (\psi - 1)t_c \right) + t_c, \tag{10}$$

where,

$$Pr[\Psi = \psi | \mathcal{T} = \text{fail}] = \frac{Pr[\Psi = \psi, \mathcal{T} = \text{fail}]}{Pr[\mathcal{T} = \text{fail}]} \tag{11}$$

and $Pr[\Psi = \psi, \mathcal{T} = \text{fail}]$ is the probability that $\psi$ is the first occupied slot and it is selected by more than one node. Therefore,
The derived equation of \( \varphi = \psi, T = \text{fail} \) is
\[
\Pr[\varphi = \psi, T = \text{fail}] = \frac{\sum_{m=2}^{N-1} \binom{N}{m} (W - \psi)^{N-m}}{W^N} + 1,
\]
where index \( m \) represents the number of nodes that selected the slot \( \psi \). Incorporating (11) and (12) into (10) yields
\[
\lambda = t_c + \sum_{\psi=1}^{w} \frac{\sum_{m=2}^{N} \binom{N}{m} (W - \psi)^{N-m}}{W^N - \sum_{f=1}^{w} (W - f)^{N-1}} (\psi - 1)t_x.
\]
The expected time spent for retrials is then found to be
\[
A = \left( \frac{1}{\xi} - 1 \right) \times \left( t_c + \sum_{\psi=1}^{w} \frac{1 + \sum_{m=2}^{N-1} \binom{N}{m} (W - \psi)^{N-m}}{W^N - \sum_{f=1}^{w} (W - f)^{N-1}} (\psi - 1)t_x \right).
\]
Hence, the expected contention delay is
\[
\Omega = A + \Lambda = \left( \frac{1}{\xi} - 1 \right) \times \left( t_c + \sum_{\psi=1}^{w} \frac{1 + \sum_{m=2}^{N-1} \binom{N}{m} (W - \psi)^{N-m}}{W^N - \sum_{f=1}^{w} (W - f)^{N-1}} (\psi - 1)t_x \right) + \sum_{\psi=1}^{w} (\psi - 1) \frac{W^N - \sum_{f=1}^{w} (W - f)^{N-1}}{W^N} t_x.
\]
The derived equation of \( \Omega \) has the following parameters: the contention window size, the number of contending nodes, one slot duration and the collision timeout duration. Since the slot duration and the collision timeout duration are network parameters that are known before the deployment, the delay optimizing CW size that minimizes the expected contention delay, \( \Omega \), which is denoted as \( W^*_t \), can be found numerically for each possible number of contending nodes based on the analysis presented and loaded to the sensor nodes as a look-up table. Note that, the derived equation can also be used to investigate the effects of different parameters on the system performance such as the effect of collision timeout duration on the expected contention delay. Although the number of contending nodes varies temporally and spatially throughout the network, different methods can be applied to approximate the optimum performance results. In Section 5.1, one such method is proposed for event-triggered WSNs.

3.2. Energy consumption for the overall contention resolution

The network lifetime maximization is another crucial objective for the wireless sensor networks. A good communication protocol needs to minimize the energy consumed for the resolution of overall contentions which corresponds to the total energy consumed by all nodes till each contending node has access to the medium. In other words, for WSN applications in which the transmission of all data is essential, to investigate the first medium access is not sufficient. Instead, one has to consider the energy consumption required for resolving all contentions.

The energy consumed for resolution of all contentions, \( E_{\text{total}} \), consists of two energy consumption components: (i) the total energy consumed for unsuccessful slot selections which results from the communications of the colliding packets and their retrials, \( E_{\text{coll}} \), and (ii) the total energy consumed for the carrier sensing in the successful slot assignments (SSA), \( E_{\text{ssa}} \).

For each contention, all of the contending nodes will choose a contention slot and listen to the medium till the first occupied contention slot. Using (5), the total energy consumed till the medium access in all successful slot assignments is found to be
\[
E_{\text{coll}}(W, N) = \frac{W}{2} t_x E_{tx} + \sum_{m=2}^{w} \sum_{\psi=1}^{w} \frac{(W - \psi)^{m-1}}{\sum_{f=1}^{w} (W - f)^{m-1}} t_x E_{tx},
\]
where \( E_{tx} \) is the energy consumed for reception per unit time, and \( m \) represents the number of contending nodes at each contention. Note that, the first component in (16) is for the case \( m = 1 \). No transmission energy is considered in \( E_{\text{coll}} \) since just the carrier sense is enough for the contention resolution in successful slot assignments.

The second energy consumption component of \( E_{\text{total}} \) is the total energy consumed for the unsuccessful communication, i.e., for the collisions and the retrials which is denoted as \( E_{\text{coll}} \). The derivation of the total energy consumed for the unsuccessful communication is similar to the derivation of the collision and retrial duration, \( \Lambda \), given in Section 3.1. However, the number of contending nodes has to be incorporated with the separation of the number of transmitting and the receiving nodes for the energy calculations. Let \( E_{\text{coll}} \) represent the expected energy consumed at one collision till its retrial. Then,
\[
E_{\text{coll}}(W, n) = \sum_{\psi=1}^{n} \sum_{m=2}^{n} \Pr[\varphi = \psi, T = \text{fail}] \theta(\psi, n, m),
\]
where \( \theta(\psi, n, m) \) is the total energy consumed for one retrial if the first selected slot is \( \psi \) and \( m \) nodes out of \( n \) select that slot which is formulated as
\[
\theta(\psi, n, m) = n(\psi - 1)t_x E_{tx} + mt_x E_{tx} + (n - m)t_x E_{tx},
\]
where \( E_{tx} \) is the energy consumed for transmission per unit time.

The total energy consumed for unsuccessful communication till the contention resolution, which is denoted as \( E_{\text{coll}} \), equals to the expected number of retrials times the expected energy consumed at one collision till its retrial, i.e.,
\[
E_{\text{coll}}(W, n) = \beta E_{\text{coll}}(W, n) = \left( \frac{1}{\xi} - 1 \right) E_{\text{coll}}(W, n).
\]
Incorporating (4), (3) and (17) into (19) yields
\[ \hat{E}_{\text{coll}}(W, n) = \left( \frac{1}{\xi} - 1 \right) \]
\[ \sum_{\psi=1}^{W} \left( \theta(\psi, n, n) + \sum_{m=2}^{n-1} \binom{n}{m} (W - \psi)^{n-m} (\theta(\psi, n, m)) \right) \]
\[ \times \frac{(W^n - n\sum_{f=1}^{n-1} (W - f)^{n-1})}{(W^n - n\sum_{f=1}^{n-1} (W - f)^{n-1})} \].

(20)

The total energy consumption till all data contentions are finished when initially there are \( N \) contending nodes is then,
\[ E_{\text{coll}}(W, N) = \sum_{n=2}^{N} \hat{E}_{\text{coll}}(W, n) \]
(21)

which is found to be
\[ E_{\text{coll}}(W, N) = \sum_{n=2}^{N} \left( \frac{1}{\xi} - 1 \right) \]
\[ \sum_{\psi=1}^{W} \left( \theta(\psi, n, n) + \sum_{m=2}^{n-1} \binom{n}{m} (W - \psi)^{n-m} (\theta(\psi, n, m)) \right) \]
\[ \times \frac{(W^n - n\sum_{f=1}^{n-1} (W - f)^{n-1})}{(W^n - n\sum_{f=1}^{n-1} (W - f)^{n-1})} \].

(22)

In (21), index \( n \) starts from 2 since a collision requires at least two nodes.

After replacing \( \xi \) and doing simplifications, the total energy consumed for unsuccessful communications till all the contentsions are resolved becomes
\[ E_{\text{coll}}(W, N) = \sum_{n=2}^{N} \sum_{\psi=1}^{W} \theta(\psi, n, n) \]
\[ + \sum_{m=2}^{n-1} \binom{n}{m} (W - \psi)^{n-m} (\theta(\psi, n, m)) \]
\[ \times \frac{n\sum_{f=1}^{n-1} (W - f)^{n-1}}{n\sum_{f=1}^{n-1} (W - f)^{n-1}} \].

(23)

Since the total energy consumed for resolving contentions of \( N \) nodes with the contention window size of \( W \) equals to the summation of expected energy consumed for the collisions and the retrials and the energy consumed for the communication in the successful slot assignment,
\[ E_{\text{total}}(W, N) = E_{\text{coll}}(W, N) + E_{\text{carrier sense}}(W, N) \]
\[ = \sum_{n=2}^{N} \sum_{\psi=1}^{W} \theta(\psi, n, n) \]
\[ + \sum_{m=2}^{n-1} \binom{n}{m} (W - \psi)^{n-m} (\theta(\psi, n, m)) \]
\[ + \frac{W}{2} t_\text{tx} + \sum_{m=2}^{N} m \sum_{\psi=1}^{W} \frac{(W - \psi)^{m-1}}{\sum_{f=1}^{m-1} (W - f)^{m-1}} t_\text{tx}. \]

(24)

The energy optimizing CW size that minimizes the energy consumed for the overall contention resolution \( E_{\text{total}} \) is denoted as \( W'_C \). Note that, the minimization of the energy consumed for the overall contention resolution does not necessarily minimizes the expected contention delay which is shown numerically in Section 4. Hence, the CW size must be optimized according to the objective of the WSN application.

4. Simulation results and the verification of the contention window size analysis

The analytical formulas derived for the minimum contention delay and the minimum energy consumption during contentions are verified via simulations using various CW sizes and various number of contending nodes, i.e., for various \( (W, N) \) tuples. At each run, the time consumed for the collisions and retrials, the carrier sense duration of the successful contention and the total contention duration, i.e., the time elapsed from the beginning of the first contention window till the successful medium access are logged for the objective of minimizing the contention delay. In addition, for the objective of minimizing the overall energy consumption during contentions, the total energy consumed by the contending nodes during collisions and retrials are logged at each run along with the total energy consumed for the carrier sense of the successful slot assignments and the cumulative energy consumed till all the contentsions are resolved.

The simulations are run for 1000 times for each parameter set in MATLAB. The communication speed is set to 20 Kbps which is the offered rate by Xbow Mica2 sensors [1]. Hence, in the simulations, \( t_r = 1 \text{ ms} \). In addition, the collision timeout is set to \( t_c = 15.15 \text{ ms} \) based on the S-MAC protocol specification where the timeout duration is defined to be the total of RTS transmission, SIFS duration and a specified processing delay which adds up to the transmission duration of 303 bits.

4.1. Contention delay results

To verify the analysis presented thoroughly; the total collision and the retrial duration, \( \lambda \), the carrier sense duration for a successful contention, \( \Gamma \), and the contention delay, \( \Omega \), values are evaluated in the simulations separately. The effect of CW size on these three performance metrics are shown in Fig. 2. The simulation results corroborate the analytical formula derived for \( \Gamma \) and \( \lambda \) as seen in the figure. As expected, a higher CW size causes longer time
to be spent for carrier sensing, i.e., for the time till the first occupied slot. On the other hand, a higher CW size also results in a decrease in the expected collision and retransmission duration since the probability of collision decreases.

The contention delay, \( \Omega \), which is found by the summation of \( I \) and \( A \) is also shown in Fig. 2. The trade-off incurred by the CW size is clearly visible. Higher CW sizes result in larger contention delays due to the longer carrier sense duration, however the smaller CW sizes also result in larger contention delays due to the higher collision probabilities. The delay optimizing contention window size, \( W' \), corresponds to the global minimum of the \( \Omega \) graph which can easily be calculated with (6) and (15). It is worth to note that the CW size used in S-MAC \([4]\) leads to 2.23 times higher average contention delay compared to the \( W' \) for the depicted \( N = 5 \) case.

The expected contention delays caused by different CW sizes are shown in Fig. 3 for 3–10 contending nodes. Fig. 3 indicates that for different number of contending nodes, the optimum CW size significantly varies. For instance, the optimum CW size is 32 and 17 for 10 and 5 nodes, respectively. If the window size of 32 is used for 5 contending nodes, then the average contention delay would be 25% larger compared to the optimum CW size of 5 nodes. One other observation is that as the number of contending nodes increases, the negative effect of high CW sizes on the expected contention delay decreases. The reason is that, more contending nodes result in an earlier occupied slot which decreases the carrier sense duration.

The SSCW method proposed in \([25]\) defines an analytical approximation to optimize the CW size as a function of the probability of collision in contentions. In order to compare the performance results, the probability of collision given in (6) is incorporated into the SSCW approximation. The contention delays obtained by setting the contention window size to the \( W' \) values found in our study is compared to the delay values obtained with the CW size defined by the SSCW approximation and the S-MAC default. Fig. 4(a) shows the delays obtained in the simulation runs where the corresponding CW sizes are given in Fig. 4(b).

As seen in Fig. 4(a), the delay optimizing window size can improve the delay significantly compared to S-MAC \([4]\) in which the CW size is defined to be a constant and compared to SSCW which calculates the CW size with approximate analysis. The CW sizes offered by SSCW form a step function which is the reason of the fluctuation of SSCW performance values in Fig. 4(a). This behavior cannot be observed in \([25]\) since the number of neighbors investigated are increased 100 nodes at a time, starting from 100 nodes. In fact, due to the limited communication range of the sensor nodes and the low deployment densities, the number of neighbors of a node is expected to be less than 20 nodes \([27]\). Moreover, the number of contending nodes will be a subset of the neighbors. It is clear from Fig. 4 that within this operational range, to use the \( W' \) as the CW size is very effective considering the contention delay.

According to Fig. 4(b), the number of contending nodes and the corresponding optimum contention window size show a linear relation which is not obvious. This relation is dependent on several network parameters. The mathematical derivations presented in this paper provide the
analytical calculations of the optimum window size values based on these network parameters.

4.2. Total energy consumption results

To verify the analysis presented for the energy consumption components of the contentsions, $E_{\text{coll}}$ and $E_{\text{tra}}$ values are evaluated in the simulations separately. The energy consumption values for transmission and reception is 27 and 10 mJ respectively in compliance with the Xbow Mica mote products [1]. The effect of CW size on the two energy consumption components is shown in Fig. 5 along with the total energy consumption incurred by the overall contentsions, $E_{\text{total}}$. As expected, higher CW sizes cause higher energy to be spent for carrier sensing till the first occupied slot. On the contrary, higher CW sizes result in lower energy consumption for collisions since the probability of collision decreases.

![Fig. 5](image-url)

**Fig. 5.** The expected energy consumption via collisions, $E_{\text{coll}}$, the expected energy consumption via carrier sense, $E_{\text{tra}}$, and the expected energy consumption of overall contention resolution, $E_{\text{total}}$, for $N = 5$.

![Fig. 6](image-url)

**Fig. 6.** Effect of contention window size for different number of contending nodes on expected energy consumption for overall contentsions (log).

![Fig. 7](image-url)

**Fig. 7.** The offered contention window sizes for SSCW, S-MAC, $W_i$, and the resulting energy consumptions.
The trade-off between the energy consumed for collisions and the energy consumed for carrier sensing is clearly visible in Fig. 5. The energy optimizing CW size, which is denoted as $W^*_E$, minimizes the total energy consumption caused by the contentions. An important observation is that the energy consumed for contentions is comparable to the energy consumed for data transmissions. As a numerical example, when the data packet size is 400 bits, the transmission of five data packets and their receptions result in 11.1 mJ of energy consumptions. However, the energy consumed for the overall contention is 7.04 mJ which is 63% of the data transmission energy requirement if the CW size is 63.

The overall energy consumption results of different CW sizes are shown in Fig. 6 for 3–10 contending nodes. As seen in the figure, the optimal operation point, $W^*_E$, gets larger as the number of contending nodes gets larger. Unlike the behavior in Fig. 3, the more the contending nodes the larger the average energy consumed, independent of the contention window size.

The energy consumed by using $W^*_E$ is compared to those obtained by using S-MAC default and the CW size calculated by SSCW in Fig. 7(a) and (b), respectively. The proposed CW sizes by the three methods are shown in Fig. 7(c). As depicted, the energy consumption is improved significantly. The energy saving due to $W^*_E$ is between 32–72% compared to S-MAC defaults for the range of 2–10 contending nodes. The gain achieved compared to the SSCW approximation is 54–74% for the same range of contending nodes.

4.3. The energy-delay trade-off

The energy consumption and delay are two important performance metrics for WSN protocols. However, since the minimization of one metric can introduce an increase in the value of the other, we end up with a trade-off between these two metrics which must be investigated separately. To depict this trade-off, the contention delay and energy consumption for overall contention values achieved by the delay optimizing CW size and the energy optimizing CW size are compared in Fig. 8. The use of energy optimizing CW size results in at most 7.5% higher average delays than the minimum delay that can be achieved with a different CW size. Likewise, the energy consumption penalty of using the delay minimizing CW size instead of the energy optimizing CW size is at most 8% for the given number of contenders range. Hence, we can conclude that using either delay optimizing or energy optimizing CW sizes presented in this paper will result in an acceptable increase in the other metric for most of the WSN applications.

5. Practical implementation of contention optimization and its impact on medium access performance

The optimum CW size values that minimize the contention delay or the energy consumption for the overall contention, $W^*_d$ and $W^*_E$ respectively, are defined to be a function of the number of contending nodes. Since in a contention-based WSN, the number of contending nodes is dynamic and cannot be known by individual sensors in advance, an approximation method is needed to benefit from the optimization method. We propose the Estimated Number of Contenders (ENCO) method which is aimed for event-triggered WSN for such applications as surveillance, environmental monitoring, disaster monitoring and target tracking.

5.1. Estimated Number of Contenders (ENCO) method

Let us assume that a certain number of sensors are deployed in a coverage area for a particular WSN application such as border surveillance. The number of nodes that can sense an event (e.g. an intruder) at an area point defines the coverage degree of that point [13]. When an event occurs in the application area, the coverage degree of the point determines the number of contending nodes assuming that every detecting node sends this information to the sink. Hence, the mean coverage degree of a deployment area approximates the average number of contending nodes.
nodes for possible events. Let the density of the deployment area be \( d \) and the sensing range of the sensors be \( R \), then, for the uniformly deployment case, the mean coverage degree \( C \) is
\[
C = \pi R^2 d.
\]
since the nodes that are at most \( R \) away can sense the event.

In the ENCO method, the mean coverage degree is used to approximate the expected number of contending nodes, which then can be used to calculate an approximate value for the optimum CW size. The mean coverage degree of a WSN can be calculated before its deployment by using the size of the target area, the number of sensors to be deployed and the sensing range of the sensors. This pre-calculated value will be used by all the sensors as the approximate number of contenders which results in a fixed and identical CW size throughout the network. To show how well the ENCO method approximates the optimum CW size results, it is tested in two different types of event-driven WSN applications: one where the event locations are independent and the other where the event locations are correlated. Let the number of contending nodes in consecutive events be represented with \( c(t) \) where \( t \) represents the event sequence. In random event location (REL) applications, the locations of consecutive events are independent. Precision agriculture is an instance of REL applications where the earth humidity or salinity levels can trigger such events. Here, \( c(t) \) is a memoryless process, i.e., consecutive number of contending nodes are not dependent on previous values. However, in correlated event location (CEL) applications, the consecutive event locations are dependent on each other such as the behavior in target tracking applications. The consecutive detection points in such applications are spatially correlated. Hence, the consecutive number of contending nodes are not independent and \( c(t) \) is not memoryless [13]. The medium access performance of the ENCO method is investigated for CEL and REL applications via simulations for 20–200 nodes that are deployed in a uniformly random manner to a 300 \( \times \) 300 m\(^2 \) area. A node can detect an event, if the event occurs within 50 m distance of the node.

5.2. Medium access performance of the ENCO method

In REL applications, events occur in different parts of the deployment area randomly. Each parameter set is simulated 1000 times. At each run, the nodes deployed to the area uniformly randomly. Afterwards, 10 event points are selected randomly and the number of nodes that detect this event is logged. The contention of the detecting nodes are simulated under three different contention window sizes: \( W_t \), \( W_{\text{ENCO}} \) and the S-MAC default where \( W_t \) and \( W_{\text{ENCO}} \) are the energy optimizing CW size for the number of detecting nodes and CW size for the ENCO method, respectively. As seen in Fig. 9(a), using \( W_{\text{ENCO}} \) results in an energy consumption very close to that which could be obtained by using \( W_t \). Hence, the ENCO method enables us setting the CW size efficiently in a distributed manner according to the network properties, namely the sensor density and the sensing range.

In CEL applications, in which the event locations have correlation, the number of nodes that detect these events, i.e., the consecutive number of nodes that will contend for the medium are not i.i.d. The consecutive detection locations result in a dependency between consecutive number of contending nodes. This dependency is studied in [28] and a packet traffic model, i.e., a model for the number of contending nodes is presented. Here, this model is used to generate the number of contending nodes for a CEL application. The model is based on uniformly random deployment and includes the parameters of the target velocity and the sensing interval which are set to 10 m/s and 1 s in this work, respectively. Number of contenders for 10 consecutive sensing are generated for 1000 different sensor deployments. The resulting contentsions are simulated under three different contention window sizes: \( W_t \), \( W_{\text{ENCO}} \) and the S-MAC default where \( W_t \) and \( W_{\text{ENCO}} \) are the energy optimizing CW size for the number of contenders and the CW size offered by the ENCO method, respectively. 

![Fig. 9. Energy consumption comparison for the overall contention resolution for (a) REL scenario and (b) CEL scenario.](image-url)
As seen in Fig. 9(b), the ENCO method enables the approximation of the theoretical optimum performance in a distributed manner for CEL applications as well.

6. Impact of ENCO method on end-to-end network performance

Contentions can be optimized for the delay incurred or for the energy consumed as shown in Sections 3.1 and 3.2, respectively. However, the end-to-end network performance is also crucial for WSNs which needs a separate investigation for the data packet transfers from source nodes to the sink. To investigate the effect of the contention optimization and the ENCO method on the end-to-end network performance, we extend our prior work that investigates the VSN performance with the currently available hardware and software capabilities [29], by incorporating the ENCO method for setting the CW size of the nodes. Video sensor networks (VSNs) are a special type of WSNs in which sensor nodes equipped with video cameras send the captured video according to the requirements of the VSN application implemented. We show that employing the CW optimization presented provides a significant improvement on the overall network performance, as well.

6.1. System model and simulation parameters

We assess the performance behavior of VSNs for currently available hardware and software capabilities in [29] where simulations are run in the OPNET simulation environment [30] with realistic parameter values. The deployment is done with a single sink node located in the geometric center of the surveillance area. Nodes are equipped with image modules composed of cameras capable of producing and compressing video images [31,32]. The raw image format is software adjustable and in our simulations SQCIF (128 × 96) format is assumed. The image module employs intra-frame encoding which results in compressed images of size 10 Kbits. Predictive encoding alternatives such as ISO MPEG or H.26× cannot practically be used in VSNs due to the high complexity involved [33]. Distributed source coding techniques are promising alternatives for encoding video in VSNs as they exploit the inter-frame redundancy with affordable complexity in the sensor nodes [34]. However, due to the lack of practical implementations yet available, we resort to the JPEG compression available on the image module. Software controlled frame rate feature allows video streams with rates between 1 and 12 fps to be introduced to the network by each individual sensor node. Event triggered data generation is simulated where the triggering event is the visual detection of the target. Since the cameras employed support the background subtraction feature, they only produce an image when the scenery changes significantly. Triggering occurs when the target is within the camera detection range of 30 m and is within the field of view (FOV) of 52 degrees. The target is assumed to move within the surveillance area according to the Random Waypoint Mobility model where the target velocity is set to 10 m/s and pause time is set to zero seconds. Crucial simulation parameters are tabulated in Table 1. Data transfer at the frame level to the sink is assumed to be done in the application layer whereas packet level communications at the MAC and routing layers are handled with S-MAC [4] and GPSR [35], respectively. Both protocols are implemented in the OPNET simulator based on their specifications.

Introducing a sleep schedule is required to increase the energy efficiency of a WSN. For traditional scalar type of data traffic, lowering the duty cycle results in a higher energy efficiency at the expense of increased delay [4]. However, in the context of video traffic, changing the duty cycle not only affects the delay but also the throughput of the system, which in turn affects the object identification or tracking quality. In general, due to the congestion in the network and the limited buffers of the sensor nodes, not all of the packets will be delivered to the data sink. For that reason, increasing the sensor video quality generated at individual nodes does not necessarily entail an increase in the received video quality at the data sink. Three different duty cycles investigated in the simulations: 0.05, 0.50, and 0.95. The latter is chosen to approximate the performance of the system where the nodes are always awake.

Table 1
Simulation parameters for VSN performance evaluation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surveillance area</td>
<td>400 × 400 m²</td>
</tr>
<tr>
<td>Network size</td>
<td>60 nodes</td>
</tr>
<tr>
<td>Deployment type</td>
<td>Uniform random</td>
</tr>
<tr>
<td>Video frame size</td>
<td>10 Kbits</td>
</tr>
<tr>
<td>Packet size</td>
<td>1 Kbits</td>
</tr>
<tr>
<td>Camera frame rate</td>
<td>1–12 fps</td>
</tr>
<tr>
<td>Field of view</td>
<td>52°</td>
</tr>
<tr>
<td>Camera detection range</td>
<td>30 m</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>250 Kbps</td>
</tr>
<tr>
<td>Buffer size</td>
<td>20 Kbits</td>
</tr>
<tr>
<td>Target mobility model</td>
<td>Random waypoint</td>
</tr>
</tbody>
</table>

Fig. 10. Effect of ENCO method on received frame rate at sink.
era frame capture rates. As shown in Fig. 10, increasing received at the sink node is investigated for different camera lost. Based on this threshold, the quality of the video can recover a frame if maximum 10% of its packets the sink. It is assumed that the video surveillance application can rate of the frames successfully received by fined by the rate of the frames successfully received by

6.2. Improving the VSN network performance with the ENCO method

The quality of video received at the sink node is defined by the rate of the frames successfully received by the sink. It is assumed that the video surveillance application can recover a frame if maximum 10% of its packets are lost. Based on this threshold, the quality of the video received at the sink node is investigated for different camera frame capture rates. As shown in Fig. 10, increasing the quality of video captured, i.e., increasing the camera frame rate can improve the quality of the video received at the sink till a certain value. By employing the ENCO method, however, the throughput of the network is increased, i.e., videos are received with higher qualities. As a numerical example, the system throughput is increased between 10% and 28% for the camera rate of 8 fps for all investigated duty cycle values.

An important application level requirement of VSNs is the successful frame delivery ratio since it signifies the reliability of the network. Simulation results for successful frame delivery ratios are depicted in Fig. 11. For almost all camera frame rate and duty cycle values, the ENCO method increases the successful frame delivery ratio. Note that, these improvements are achieved without incurring any overhead, but with just setting the default CW size wisely.

A crucial performance metric for both VSNs and WSNs is the latency, i.e., the end-to-end delay observed. Fig. 12 shows the effect of the ENCO method on the latency values achieved. As seen in the figure, for all camera frame rates and duty cycle values, latencies are decreased when the ENCO method is applied along with the delay optimizing CW size for the average coverage degree. The effect is higher for the lower duty cycles. As seen from the figure, the latency is improved between 20% and 35% for duty cycle of 0.05 for different camera frame rate values.

The ENCO method can improve both latency and throughput values of the network without incurring any overhead as shown in the simulation results. Since the ENCO method is not specific to a certain MAC protocol, it can be applied to any MAC protocol that employs slotted-CSMA. Although the ENCO method defines a static and network-wide CW size setting, it improves the network performance considerably. This improvement can be increased by spatial settings such as by a method that considers the number of neighbors for the CW size decision. Alternatively, a spatio-temporal method can result in better performance, for instance, one that considers the history of the number of contending nodes. All of these methods can use the contention window size optimizations presented.

7. Conclusion and future work

Due to the limited battery capacities of the sensor nodes, minimizing the energy consumption is a crucial objective for all WSN studies. For the delay-sensitive applications such as disaster monitoring and target tracking, the minimization of the communication delay is another critical objective. Although there exist studies proposing CW adjustment methods for IEEE 802.11, a distinctive CW size setting method is still required for WSNs since the binary exponential backoff (BEB) is not preferred in WSNs due to its exponential size increase. Moreover, the CW size studies for IEEE 802.11 focus on improving the fairness or the throughput which are not the main objectives of WSNs. Instead, the minimization of the energy consumption is aimed in WSNs due to the limited battery capacities of the sensor nodes.

In this paper, we show the significance of the contention window size setting on these two metrics both analytically and by simulations. With the analyses presented, the energy optimizing contention window size or the delay optimizing contention window size can be calculated depending on the primary objective of the network. It is shown that the performance of contention-based MAC protocols can be significantly improved using the corresponding optimum contention window size. The presented analysis and optimizations are also applicable to other wireless networks that define a fixed contention window size and uniformly random contention.
The Estimated Number of Contenders (ENCO) method is proposed for event-triggered WSNs in which the optimum contention window size can be approximated by individual sensor nodes in a distributed manner. Main idea of the ENCO method is using the mean coverage degree of the network which is a function of the network properties, namely, the sensor density and the sensing range. The simulations show that this method achieves close to the optimum performance results obtained by using the corresponding optimal contention window sizes. Additionally, the simulations performed to investigate the end-to-end network performance show that the ENCO method decreases the end-to-end delay and increasing the system throughput at the same time, without incurring any overhead. As a future work, local information such as the number of neighbors will be embedded into the contention window size setting mechanism to improve the performance of the proposed method.

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References

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