IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received January 3, 2021, accepted January 9, 2021, date of publication January 19, 2021, date of current version January 29, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3052955

A Distributed Surveillance System With Full Coverage Guarantee Using Positive Orthogonal Codes

MAAZEN ALSABAAN[1], WALEED ALSMARY[2], (Senior Member, IEEE), ABDULAZIZ ALQUNIAH[1,3], MOHAMED MAHMOUD[4], (Senior Member, IEEE), AND MAHMOUD NABIL[5]

[1]Computer Engineering Department, College of Computer and Information Sciences, King Saud University, Riyadh 11543, Saudi Arabia
[2]Computer Engineering Department, College of Computer and Information Systems, Umm Al-Qura University, Makkah 24381, Saudi Arabia
[3]Communication and Information Technology Research Institute, King Abdulaziz City for Science and Technology, Riyadh 12354, Saudi Arabia
[4]Department of Electrical and Computer Engineering, Tennessee Tech University, Cookeville, TN 38505, USA
[5]Department of Electrical and Computer Engineering, North Carolina A&T University, Greensboro, NC 27411, USA

Corresponding author: Maazen Alsabaan (malsabaan@ksu.edu.sa)

This work was supported by the National Plan of Science, Technology and Innovation (MAARIFAH), King Abdulaziz City for Science and Technology, Saudi Arabia, under Award 15-INF3775-02.

ABSTRACT Surveillance systems provide continual coverage of target area(s) using several cameras through different angles. Conventionally, a central unit controls the system by adjusting the coverage rate of the cameras. However, in large-scale environments, such a centralized system is costly and energy inefficient, as the central unit should exchange a lot of control messages with the cameras. Centralized systems also are not resilient because they fail when the central unit is faulty. In this paper, we propose a distributed surveillance system in which each camera independently decides its activation sequence without exchanging control messages while providing guaranteed coverage of the target areas and ensuring a fault-tolerant system. Our goal is to provide full coverage of all target areas with reduced number of activations of each camera to reduce energy consumption and increase the system lifetime in case of wireless camera sensor network (WCSN) where cameras are battery-powered. To achieve that goal, each camera is activated according to positive orthogonal codes (POCs). POCs have been used for medium access control (MAC) in vehicular sensor networks as a distributed solution for medium access to reduce packet collisions. To the best of our knowledge, this is the first work that uses POCs to create a distributed surveillance system. This work proposes the system design, modeling, and simulation study of a POC-based distributed surveillance system. Moreover, we present a performance evaluation for the coverage percentage and coverage cost metrics using simulations and theoretical analysis. The results indicate that the use of POCs can achieve full coverage of the target areas with a significantly reduced number of cameras compared to a benchmark scheme that uses synchronous fixed repetition (SFR) codes.

INDEX TERMS Distributed surveillance, guaranteed coverage, positive orthogonal codes, synchronous fixed repetition.

I. INTRODUCTION

Wireless camera sensor networks (WCSNs) have gained extensive interest in wireless multimedia sensor networks (WMSNs) because they enable new applications to the existing wireless sensor network (WSN). One of these applications is video surveillance, which is in high demand in fields ranging from civil applications to highly sensitive military applications [1]. The challenges and limitations of this technology have been the focus of the research community. For example, target coverage is a crucial requirement for surveillance applications in both open areas (e.g., streets) and closed areas (e.g., shopping malls, airports, and hospitals). In surveillance applications, targets must be continuously covered by different cameras through different angles. Currently, wireless cameras are well designed, secure, and efficient. The target coverage problem traditionally aims to optimize the activation of cameras to ensure the full coverage of all targets.

One common solution to this problem uses a centralized unit to control the surveillance system by adjusting the coverage rate of the cameras. However, in large-scale environments, such a centralized system is costly and energy

The associate editor coordinating the review of this manuscript and approving it for publication was Wei Wei.

inefficient, as the central unit needs to exchange a lot of control messages with the cameras. Centralized systems also suffer a single point of failure and attack. The system fails when the central unit is faulty or being attacked, e.g., by Denial of Service (DoS) attacks. Moreover, in some applications, wireless cameras are energy-limited, especially when used to cover large-scale areas. In these applications, a distributed solution is required to eliminate the transmission of control messages with a central unit.

Hence, a distributed surveillance system is required to create a resilient and efficient surveillance system. The challenge here is that instead of making central activation decisions for the cameras, each camera should independently decide its activation sequence (without exchanging control messages for efficiency) that guarantees the full coverage of the target area(s). The other challenge is that a distributed camera sensor network (DCSN) is energy-constrained, where the activation of each camera reduces its battery lifetime, so the activation sequence should not only ensure that the target area is fully covered but also the system consumes low energy by reducing the number of active cameras to increase the lifetime of the network.

In this paper, we propose a scheme to enable the wireless cameras in wireless camera sensor networks to perform the required surveillance in a distributed fashion. In these networks, energy consumption and bandwidth are critical constraints, as nodes are battery-powered and data are sent over a limited wireless bandwidth. Our goal is to reduce the number of activations of each camera to increase its lifetime while providing coverage of all target areas without exchanging control or coordination messages among the cameras. To achieve that goal, positive orthogonal codes (POCs) can be utilized to support the energy-efficient coverage of target areas.

Random repetition codes schemes such as POCs and synchronous fixed repetition (SFR) have been used for medium access control (MAC) in vehicular sensor networks as a distributed solution for medium access to reduce packet collisions [22]–[30]. These codes are used to enable several vehicles to coordinate the use of a shared wireless communication channel in a distributed fashion while ensuring high usage of the channel and low number of collisions, i.e., concurrent transmission. Inspired by this research area, in this paper, we investigate the use of POCs and SFR codes to create a distributed surveillance system with full coverage guarantees. Although, SFR scheme generates the codes randomly without any guarantees, we use it as a benchmark scheme. To the best of our knowledge, this is the first work that proposes a distributed surveillance system using POCs to create a low-energy, efficient, and resilient system with coverage guarantee.

This work proposes the system design, modeling, and simulation study of a POC-based distributed surveillance system. The main contributions of this paper are as follows: (I) it provides a theoretical study of the distributed coverage problem using POC, (II) it presents a theoretical analysis for the distributed coverage algorithm, and (III) it offers a comparison between the proposed POC-based scheme versus a simple approach that uses SFR. Each contribution includes subtasks and results that support the main goal of this work. The first two parts of this work provide the theoretical foundation of the mathematical optimization formulation, a probabilistic analysis of the coverage problem, and the worst-case bounds of coverage. The third part demonstrates the efficiency of the proposed POC-based scheme compared to the SFR-based scheme.

Extensive performance evaluations using simulations and theoretical analysis that focused on the coverage percentage and coverage cost metrics have been conducted. The results indicate that the use of POCs can achieve a high coverage percentage efficiently and the POC-based scheme can cover the targeted areas with fewer cameras comparing to the SFR-based scheme.

The remainder of this paper is organized as follows. Section II discusses the related works. Preliminaries are discussed in Section III. Section IV explains the system model considered in this paper. Section V explains the proposed distributed surveillance scheme. Sections VI and VII provide a comprehensive analysis and evaluation of the proposed scheme and compare it to the benchmark scheme. Specifically, probabilistic analysis is given in Section VI, and simulation results are discussed in Section VII. Finally, Section VIII concludes the paper and provides future works.

II. RELATED WORKS

The surveillance systems have been investigated in the research community [2]–[9] in the context of WSNs in terms of connectivity, coverage, and networking metrics. They have also been investigated from different perspectives including optimizing sensor placement and movement and scheduling sensor activity [10]–[12]. Target coverage is an important performance metric in sensor networks, which quantifies the quality of service (surveillance) or how well a sensor field is monitored [10]. Sensor network coverage has been studied in the literature [10], [11] from various perspectives (e.g., placement, selection, and detection).

An overview of the related research works is given in Fig. 1. The figure shows that the infrastructure for communication can be wired or wireless. The focus of this paper falls under the wireless infrastructure. Moreover, the system can be centralized or distributed. The focus of this research falls under the distributed surveillance as the centralized formulation usually uses fixed image/video capturing rate, which results in constant camera activations.

In [10], different types of coverage problems were surveyed in sensor networks. The study defines three categories of coverage problems according to the subject to be covered: target, area, and barrier. In target coverage problems, targets are modeled as a set of discrete space points in the sensor field. Area coverage problem equally treats every point in the sensor field. Barrier coverage constructs a barrier for finding a penetration path across the sensor field with some

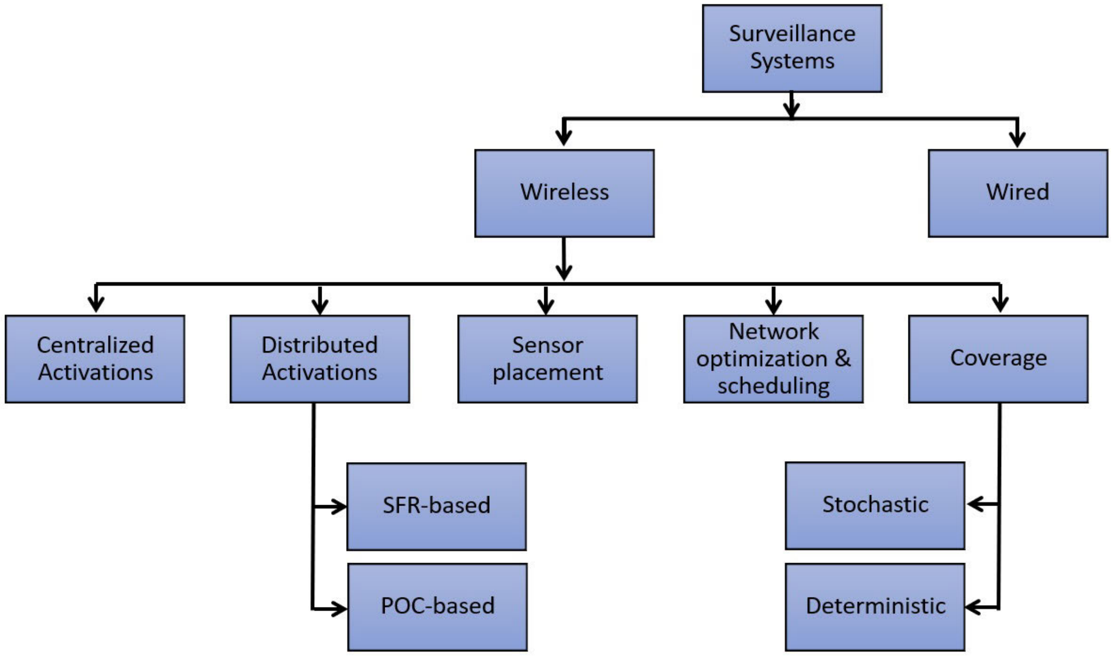

FIGURE 1. Overview on related research works.

desired coverage characteristics. The study also investigates the random deployment of sensors and how random activity scheduling of sensors could prolong the operation time and satisfy the coverage requirements. The approach for activity scheduling requires exchanging messages between the nodes. Random independent sleeping (RIS) has also been studied, where each sensor independently decides its activity depending on parameter p, which must be calculated based on the area and number of sensors. Another issue with this procedure is the lack of full coverage.

The coverage problem has been defined from several perspectives including deterministic and stochastic in [11]. In deterministic coverage, the area shape must be predefined; one example of uniform deterministic coverage is grid-based sensor deployment, where nodes are located on the intersection points of a grid. In many situations, deterministic coverage is not practical nor feasible, and thus stochastic coverage is applied, where sensors are randomly distributed throughout the environment.

Several works have investigated the placement of sensors to enhance coverage [12], but such methods address only stationary sensors or the initial placement of mobile sensors. During node placement, the coverage areas of the sensor nodes may overlap, causing redundancy. This redundancy can be reduced (or eliminated) by scheduling the sensor activity. Scheduling here refers to the order and timing of turning a sensor on or off for a particular time frame. Scheduling should incorporate sensor placement to reduce redundancy to the greatest extent possible. This is usually performed by first identifying any overlap in the coverage area, followed by sensor activity scheduling [11].

Large-scale area monitoring is a challenging engineering task due to the scale and heterogeneity among sensors, algorithms, and visualization levels [33]. Traditional surveillance systems use wired links to implement a centralized network, which implies fewer restrictions regarding storage and energy sources. In many applications, the wired systems result in high installation and maintenance costs. The rapid advancement in camera and sensor technology, embedded system design, and wireless communications has enabled wireless camera sensor networks (WCSNs), with the advantages of easy installation and scalability. In WCSNs, energy consumption and bandwidth are critical constraints, as nodes are battery-powered and data are sent over a limited wireless bandwidth.

Traditionally, a centralized architecture is used for WCSNs where a centralized unit controls the surveillance system by adjusting the coverage rate. However, in large-scale environments, such a centralized system is energy inefficient, as the transmission of continuous control and coordination messages between the central unit and cameras is a source of extra energy consumption. Centralized systems also suffer from a single point of failure and attack. The system fails when the central unit is faulty or being attacked, e.g., by Denial of Service (DoS) attacks. Hence, a distributed surveillance system is necessary for large-scale areas to create a resilient and efficient system.

Several works have modelled target coverage [17]–[20]. In [20], the coverage is traded for network lifetime, where the lifetime is considered as a constraint and the coverage is optimized. In [17], the coverage problem has been investigated in directional sensor networks in which sensors have tunable directions and can only cover one direction at a time. A distributed greedy algorithm is proposed to assign directions to the sensors such that the number of target points in the sensing area is maximized.

In another research area, random repetition codes schemes such as SFR, POCs, and optical orthogonal codes (OOCs) have been used for medium access control (MAC) in vehicular sensor networks as a distributed solution for communication channel access to avoid packet collisions [22]–[30]. These codes are used to enable several vehicles to coordinate the use of a shared wireless communication channel in a distributed fashion while ensuring high usage of the channel and low number of packet collisions, i.e., concurrent transmission. Inspired by this research area, in this paper, *we investigate the use of POCs and SFR codes to create a distributed surveillance system with full coverage guarantee.*

The use of POCs in MAC schemes have shown significant improvements in delivering information and reducing packet collisions in vehicular networks in a distributed manner [25]. In the surveillance application, POCs are used to control the activations of cameras in a distributed way. The analogy between the surveillance application and MAC scheme is that packets can be mapped to camera activations, and collisions can be mapped to coverage redundancy. On one hand, while in MAC scheme, the POC reduces collisions in vehicular networks while guaranteeing packet delivery, the POCs in the surveillance system are used to reduce the redundancy in the activations of the cameras (which reduces the energy consumption) and guarantee coverage of the target areas.

Although, SFR scheme generates the codes randomly without any guarantees, we use it as a benchmark scheme. To the best of our knowledge, this is *the first work that proposes a distributed surveillance system using POCs and SFR codes to create a low-energy, efficient, and resilient system with coverage guarantee.*

III. PRELIMINARIES

Recently, several repetition-based MAC protocols have been proposed for broadcasting of safety messages in VANETs [32]. Building upon a time-slotted system, a transmission frame is divided into several time slots, where each time slot corresponds to the transmission time of a single safety packet. In each time slot, each vehicle either broadcasts a message or listens for transmission from other nodes. The idea is that by repeating the transmission of a safety message multiple times during a time frame, the variation in the transmission time helps mitigate the harsh channel conditions in VANETs.

The transmission time slots are selected in each frame using various probabilistic means for distributing the transmission opportunities of vehicles across the time frame, thereby reducing the chance of message collisions with neighboring vehicles and hidden terminals without using extra control or coordination messages. For instance, in SFR, each vehicle randomly selects a fixed number w of the L time slots in a frame for transmitting messages, while in Synchronous p-Persistent Repetition (SPR), a vehicle transmits its message in each time slot with probability p.

Farnoud *et al.* have extended the repetition-based MAC schemes by using structured transmission patterns based on POCs [23], [25]. POCs are families of binary codewords with length L and constant weight w, where w is the number of 1's in each codeword. Each codeword is used for one time frame where each bit in the codeword corresponds to one time slot. The codeword determines the transmission pattern in each time frame where the vehicle transmits a packet in a time slot when the corresponding bit in the codeword is one.

TABLE 1. Example of orthogonality vs. pseudo-orthogonality codes, $L = 4$ and $w = 2$.

Orthogonal	Pseudo-orthogonal $\lambda = 1$
1100	1100
0011	1010
	1001
	0110
	0101
	0011

These codewords have constraints on the auto-correlation and/or the cross-correlation [34]. There are two types based on that: synchronous and asynchronous. In the synchronous POC, the cross-correlation between any two codewords is at most λ, i.e., given that a and b are two different codewords in a POC of length L and weight w, then

$$\sum_{i=1}^{L} a_i b_i \leq \lambda \tag{1}$$

While the asynchronous POC, which is known also as optical orthogonal code (OOC) [35], has the following two conditions: (1) the cross-correlation between any two codewords should be at most λ; (2) the autocorrelation of each codeword should be at most λ. The study of these codes was first motivated by multiple access researchers for CDMA, and it has been proved that they can increase the efficiency of multiple access. The OOC found its way into different applications, such as mobile radio, FDMA, and radar signals design.

If two codes are orthogonal, that means they do not interfere, $\lambda = 0$, which makes the number of possible codewords only L/w; but if two codewords are pseudo-orthogonal and $\lambda = 1$, then there is one interfering (or overlapping) between the two codewords. Interfering bit is a bit with a binary value of 1. However, the number of codewords will be up to:

$$\left\lfloor \frac{L}{w} \left\lfloor \frac{L-1}{w-1} \right\rfloor \right\rfloor \tag{2}$$

For example, if $L = 100$ and $w = 5$, with orthogonal codes only 20 codewords can be obtained. Meanwhile, in pseudo-orthogonal, up to 480 codewords could be obtained. Table 1 gives an example to clarify the difference between orthogonal and pseudo-orthogonal POCs for $L = 4$ and $w = 2$. In orthogonal, only two codewords could be obtained, while pseudo-orthogonal with $\lambda = 1$ can give up to 6 codewords.

The analytical studies and simulations given in [23], [25] indicate that the POC-based MAC schemes attain lower probabilities of reception failure than random repetition schemes such as SFR.

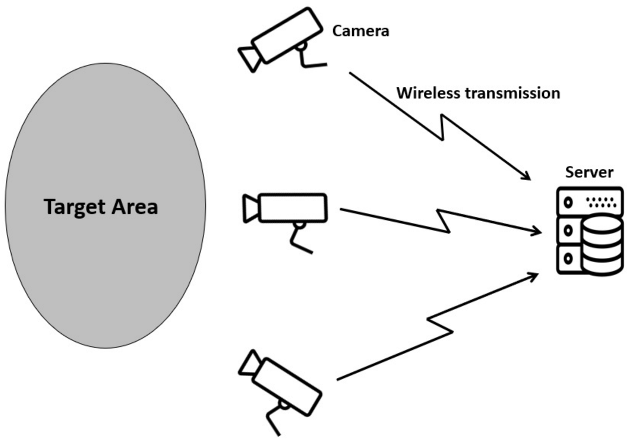

FIGURE 2. An illustration of the system model considered in this paper.

IV. SYSTEM MODEL

In our application, we consider a large-scale surveillance system in which there exists a large number of cameras that are required to cover large areas for a long period of time. In our system model, a distributed surveillance system that monitors the target areas is considered. As shown in Fig. 2, the system model considered in this paper has a storage server and several wireless cameras. The wireless cameras can communicate with the storage server to transfer the information captured by the cameras using wireless communications. The cameras do not communicate with each other. They capture images with a certain sampling rate during the system time frame, where the sampling rate is identical for all cameras. For better resilience, the system can have more than one storage server.

This type of application can be set on a fixed capture rate, which consumes huge bandwidth, significant energy, and might cause communication loss, so we consider a random rate. Denote the lifetime of surveillance operation by T, during which the cameras can be activated multiple times as required by the surveillance application. T is divided into F time frames, where the time frame lengths are equal and specified by the application. Each time frame is divided into L time slots, where the sampling ratio is defined according to the application; the length of a time slot is also defined by the application. M cameras are assumed to be fixed and can be randomly distributed so that there is a minimum number of cameras M_{min} that can guarantee full coverage of the area (i.e., space domain) if they are alternately active during the surveillance operation lifetime (i.e., coverage over time domain).

Full coverage is achieved when at least one camera is active in each time slot in the time frame. During each time frame, each camera uses an activation code that guarantees the coverage of the target area with low energy consumption. Our proposed scheme addresses coverage over the time domain. We assume M cameras and F to be one time frame for simplicity.

V. PROPOSED DISTRIBUTED SURVEILLANCE SCHEME

We propose a scheme for activating cameras independently for a distributed surveillance system. Our scheme aims to reduce the number of sensing times (actual activation times) by using positive orthogonal codes as activation patterns for cameras. The proposed scheme activates cameras without the need for a central controller or information exchange between cameras, with guaranteeing the full coverage of the target area.

A. REPETITION-BASED PROTOCOLS

1) ACTIVATION PATTERNS

We develop a surveillance system that guarantees full coverage over time with low energy consumption and enhanced communication quality of service (QoS) using a distributed topology, where there is no central controller or exchange of control messages. In the proposed system, no extra motion-sensing hardware is required. Cameras are independently activated to reduce collisions between the transmitted and retransmitted messages of different cameras in case of exchanging messages to coordinate the activation of the cameras, which improves the QoS of the communications and reduces energy consumption. We also develop a mechanism that provides minimum activations per camera for the entire surveillance system, which decreases the energy consumption of the entire system. The most important advantage in our proposed system is that it enhances the communication QoS and guarantees full coverage with a minimum number of cameras.

Repetition-based broadcast protocols depend on repeating a message multiple times in small intervals (i.e., shorter than its lifetime) to ensure the high probability of reception [31]. Our proposed model for camera activation depends on this strategy. Cameras are activated multiple times during the system lifetime to ensure the high probability of area full coverage with a low probability of redundant activations (i.e., two or more cameras are active at the same time). To achieve that in our system, we use two random repetition code schemes (SFR and POC) that are used successfully in medium access control protocols.

2) SYNCHRONOUS FIXED REPETITION (SFR)

In SFR, each camera is activated w times in each frame; these w times are randomly selected from the L available time slots. SFR performs well in harsh channel conditions in communication, but selecting activation times randomly and without restrictions may increase redundant activations, which increases the number of cameras required to guarantee full coverage for the target area.

3) POSITIVE ORTHOGONAL CODES (POC)

One method to decrease redundancy in coverage is by decreasing the redundant active slots between any two cameras. POC can provide this advantage with using the cross-correlation condition, as will be discussed in the next section.

B. CODE GENERATION PROCEDURES

In our system, an activation pattern should be assigned for each camera. We name this activation pattern "*codeword*", and the length of that codeword is equal to the number of time slots L. The codeword is a binary code with L elements, where each element is either 0 or 1. The number of codewords required is equal to the number of cameras M. All codewords are collected together in a "*codebook*" matrix, with M rows and L columns. Choosing L and w is our main concern, so they should be determined such that the M cameras of the system can fully cover the target areas.

1) SFR CODE GENERATION

The process of generating a codeword using SFR scheme is as follows. If the number of activations in the L time slot is w, the SFR scheme can generate a codebook with up to $\binom{L}{w}$ codewords, which means that the number of cameras can be up to $\binom{L}{w}$ without code repetitions and the number of activations (i.e., the number of ones in each codeword or w) is distributed randomly over the codeword. In our model, codes are not repeated, and the number of generated codes is sufficient.

2) POC GENERATION

The generation of POCs is much more complex than the generation of SFR codes, because the codewords should satisfy the cross-correlation condition. In POC, in addition to defining L and w, we define a cross-correlation parameter, λ, which is a fixed integer that represents the relationship between any two codewords. When $\lambda = 1$, which is usually chosen, any two cameras have, at most, one redundant active time slot. In SFR, the number of redundant active time slots can be up to $(w - 1)$. There are many studies on optimal POC generation, which occurs when all possible codewords are obtained, (||C||). Johnson [31] defines the upper bound for the number of possible codewords that can be generated by the POC scheme as follows:

$$||C|| = \left\lfloor \frac{L}{w} \left\lfloor \frac{L-1}{w-1} \cdots \left\lfloor \frac{L-w+\partial}{\partial} \right\rfloor \cdots \right\rfloor \right\rfloor \tag{3}$$

where $\lfloor x \rfloor$ is the largest integer that is less than or equal to x and $\partial = (w - \lambda)$.

In our work, λ is equal to 1, which makes the number of codes in case of optimal code generation as follows:

$$||C|| = \left\lfloor \frac{L}{w} \left\lfloor \frac{L-1}{w-1} \right\rfloor \right\rfloor \tag{4}$$

Thus, for example, if $L = 8$ and $w = 3$, the possible number of POC codewords is six, i.e., a 6×8 codebook can be generated compared to a 56×8 codebook in case of using SFR.

In our proposed system, we do not target the optimal code generation; instead, our target is to generate codes assigned to sufficient number of cameras to ensure full coverage of the target area. To do that, the generation of the POC is given in the pseudo-code of Algorithm 1. The algorithm works as follows:

Algorithm 1: POC Generation

```
Input:  L, w, λ
Output: Codebook that has activation codes
        that are cross-correlated.
// Define two arrays called Codes and
   Codebook.
Codes = [];
Codebook = [];
// Generate all possible codewords ((L choose w)
   codewords) and store them in Codes.
   Each codeword has L bits and w ones in
   random locations.
Codes = Generate_Random_Codewords(L,w);
// Add the first codeword in Codes to
   Codebook.
Codebook.Append(Codes[1]);
// Add to Codebook, the codewords that have
   a hamming distance with Codes[1] ≥
   2(w−λ)
for i ← 2 to (L choose w) do
    // Compute the hamming distance for
       Codes[1] and Codes[i] using Hamming()
       that returns the hamming distance.
    d = Hamming(Codes[1],Codes[i]);
    if d ≥ 2(w−λ) then
        Codebook.Append(Codes[i])
    end
end
// Remove a codeword from Codebook if its
   hamming distance with any other
   codeword is less than 2(w−λ).
for i ← 2 to len(Codebook) − 1 do
    for k ← i+1 to len(Codebook) do
        d = Hamming(Codes[i],Codes[k]);
        if d < 2(w−λ) then
            Codebook.Remove(Codes[k])
        end
    end
end
Result: Codebook that has activation codes
        that are cross-correlated.
```

The idea is to randomly generate $\binom{L}{w}$ codewords, as in SFR, and then add the first codeword to a new codebook and compare it with all other possible codewords. These codewords are added to the new codebook if their Hamming distance is larger than or equal to $2\delta = 2(w - \lambda)$. The Hamming distance of two codewords is the number of bit positions in which the two bits are different. Therefore, all codewords have a true cross-correlation with the first codeword. From the new codebook, this process is repeated with the second, third and subsequent codewords to the last codeword. By performing these steps, ultimately the POC codebook is created.

To more clarify the POC generation process, a numerical example is given in Figure 3. In this example, $w = 3$ and $\lambda = 1$ so the Hamming distance between any two codewords should be at least $2(w - \lambda) = 4$. As shown in the figure,

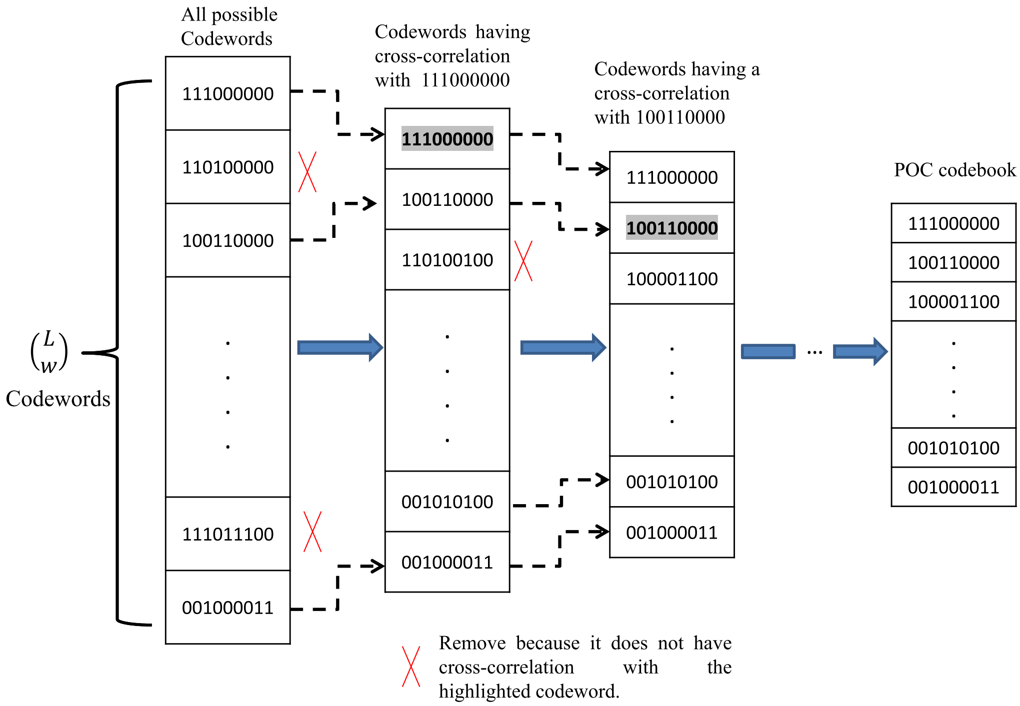

FIGURE 3. An illustration of the POC generation process, which shows how the algorithm starts from the entire dictionary and then extract the pseudo-orthogonal codes that are cross-correlated.

first, $\binom{L}{w}$ random codes are generated to obtain all possible codewords, which constitutes the first round of codewords. Then, the first code 111000000 is added to the second round of codewords, and then the hamming distances of this code and all other codes in the first round of codewords are calculated. A codeword is removed if the hamming distance is less than 4, and it is added to the second round of codewords if the hamming distance is at least 4. For instance, the codeword 110100000 is removed because the hamming distance between 110100000 and 111000000 is 2, while the code 100110000 is added to the second round of codewords because the hamming distance between 100110000 and 111000000 is 4. These steps should be repeated on the code 100110000 to make the third round of codewords. By doing these steps on all codewords, any pair of codewords in the final round of codewords should have cross-correlation. The codewords of the final round is the POC codebook that is used by our system.

VI. THEORETICAL ANALYSIS

This section presents the theoretical foundation of the mathematical formulation, probabilistic analysis of the coverage problem, and worst-case bounds.

The target area is fully covered if there is at least one active camera per time slot. The area is partially covered if one or more time slots are uncovered. For example, if $L = 10$ and 8 time slots are covered, then that area is 80% covered. The area is covered if all time slots (TS_i) are covered:

$$TS_1 \cap TS_2 \cap \cdots \cap TS_L \tag{5}$$

A time slot is considered covered if at least one camera (S_i) is active in that time slot:

$$S_1 \cup S_2 \cup \cdots \cup S_M \tag{6}$$

Probability of Coverage is defined as the number of covered time slots (i.e., each one is covered by at least one camera) divided by the number of all time slots L. The area is considered *uncovered* if one or more time slots are uncovered. In this section, we derive mathematical formulas for the probability of coverage for SFR and POC based schemes.

A. PROBABILITY OF COVERAGE FOR THE SFR-BASED SCHEME

In SFR, there are w activations per camera, which are randomly distributed over the time slots. The codeword or camera activation patterns are assumed to be independent. No auto or cross-correlation conditions are defined, so the chance of redundant activations per time slot increases.

The probability that a certain camera is not activated at $TS_1, TS_2, \ldots,$ or TS_k slots is equal to:

$$\frac{\binom{L-k}{w}}{\binom{L}{w}} \tag{7}$$

where the activation pattern of a camera can be any of $\binom{L}{w}$ patterns with equal probability. Among these possible patterns, $\binom{L-k}{w}$ patterns do not include coverage in k time slots, which can provide the *uncoverage* probability, P_u. If one or more time slots are uncovered, the area is uncovered. Let's set $k = 1$, which gives the probability that at least one time slot is uncovered as follows:

$$\frac{\binom{L-1}{w}}{\binom{L}{w}} \tag{8}$$

TABLE 2. 1's distribution for POC codewords.

	w	$L-w$
First codeword	1111· · ·111	000· · ·00
	1000· · ·000	XXX· · ·XX
	0100· · ·000	XXX· · ·XX
	· · · · · ·	· · · · · ·
	0000· · ·001	XXX· · ·XX
		P_1

Because there are M cameras and they are independent, P_u is computed as follows:

$$P_u = \left(\frac{\binom{L-1}{w}}{\binom{L}{w}} \right)^M \tag{9}$$

Hence, to achieve coverage probability P_c, which is the probability that all time slots are covered during time frame L, $P_c = 1 - P_u$ is computed as follows:

$$P_c = 1 - \left(\frac{\binom{L-1}{w}}{\binom{L}{w}} \right)^M \tag{10}$$

B. PROBABILITY OF COVERAGE FOR THE POC-BASED SCHEME

Following the same procedure used in the SFR-based scheme to compute the probability of coverage, the probability of one uncovered slot is computed first, but the cross-correlation condition makes the POC analysis more complex.

Table 2 shows the codewords after reordering them. By putting the 1's together, w ones are obtained; by putting the 0's together, $(L-w)$ 0's are obtained. The first row represents the first codeword. $(L-w)$ represents the uncovered slots for the first codeword.

From the POC cross-correlation definition with $\lambda = 1$, only one active bit (i.e., an activation or 1) is placed under w, while the remaining $(w-1)$ bits are placed under $(L-w)$. With $\lambda = 1$, any two cameras can have a redundant activation in only one time slot. Thus, the probability of having one in a time slot over $(L-w)$ slots is:

$$\left\lfloor \frac{w-1}{L-w} \right\rfloor \tag{11}$$

The number of codewords that can have a time slot with no overlap ($\lambda = 0$) is as follows:

$$\left\lfloor \frac{L-w}{w-1} \right\rfloor \tag{12}$$

As described in Johnson bounds, to have POC with no overlap, possible codewords are $\frac{L}{w}$. Therefore, the probability that a camera covers a time slot where no other camera covers the same slot, P_1, is:

$$P_1 = \frac{\left\lfloor \frac{L-w}{w-1} \right\rfloor}{||C||} \tag{13}$$

TABLE 3. Parameters used to compute codewords and codebooks for POC and SFR.

L	Versions	w
20	200	3
	200	4
	200	5
22	200	3
	200	4
	200	5
	200	3
24	200	4
	100	5

where ||C|| is the number of total codewords. We depend on the optimal number of codewords and the possible number that can be obtained from the simulation.

Now, the probability of having a time slot uncovered by this camera is calculated by subtracting Eq. 13 from one to obtain:

$$1 - P_1 \tag{14}$$

The probability of having a time slot uncovered by M cameras is:

$$P_u = (1 - P_1)^M \tag{15}$$

As explained in the derivation of probability of coverage of SFR-based scheme, $1 - P_u$ is the probability of coverage, so

$$P_c = 1 - (1 - P_1)^M \tag{16}$$

VII. SIMULATION RESULTS

This section provides numerical results for our simulations to the proposed scheme. Due to the distributed nature and independent activation decision of our proposed scheme, it can undoubtedly improve QoS of the communication because it significantly reduces the collisions of messages by eliminating many control messages and retransmissions. Our main objective is to examine the coverage of POC activation patterns and compare it to the coverage of SFR. L and w are selected to minimize the number of activations. To do that, the value of w should be small, whereas L should be large enough to generate sufficient number of codewords. Table 3 summarizes our choice for L and w for both SFR and POC. In our simulation, the positions of the w ones in the codewords are selected randomly.

A. COVERAGE PERCENTAGE

As previously explained, an area is considered fully covered if all slots are covered; the slot is covered if it has at least one active camera. Multiple versions of codebooks (200 versions on average) are generated, where each codebook contains multiple codewords and each codeword is used for a camera's activation pattern. For each version of the codebooks, the coverage vector is calculated, which has length L. Each element is the sum of activations per time slot; if the element value is more than one activation, it implies that this time slot is covered.

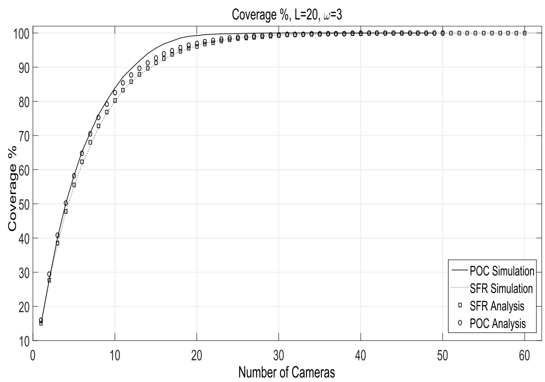

FIGURE 4. **Coverage percentage of POC and SFR based schemes versus number of cameras for $L = 20$ and $w = 3$.**

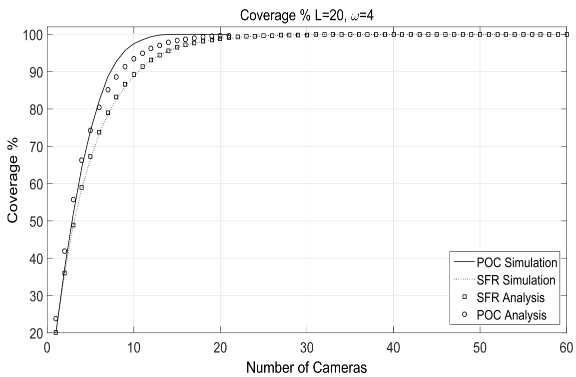

FIGURE 5. **Coverage percentage of POC and SFR based schemes versus number of cameras for $L = 20$ and $w = 4$.**

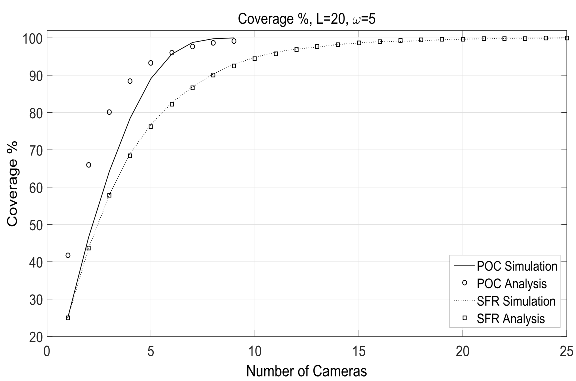

FIGURE 6. **Coverage percentage of POC and SFR based schemes versus number of cameras for $L = 20$ and $w = 5$.**

Then, the coverage percentage is calculated as the number of covered time slots divided by the total number of time slots. After calculating the coverage percentage for all versions, the average coverage percentage is calculated and plotted for both SFR and POC based schemes. Figures 4-12 give the coverage percentage versus the number of cameras at different values of L and w for both POC and SFR schemes. Each figure gives the coverage percentages computed by the analytical equation and resulted from the simulation.

Figures 4, 5 and 6 give the coverage percentage versus the number of cameras for $L = 20$ at $w = 3$, 4, and 5, respectively. In the figures, it can be seen that the POC-based

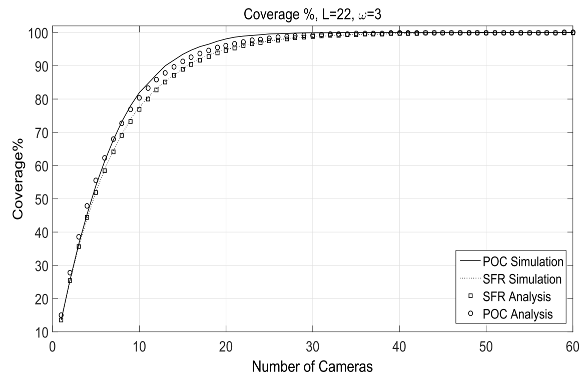

FIGURE 7. **Coverage percentage of POC and SFR based schemes versus number of cameras for $L = 22$ and $w = 3$.**

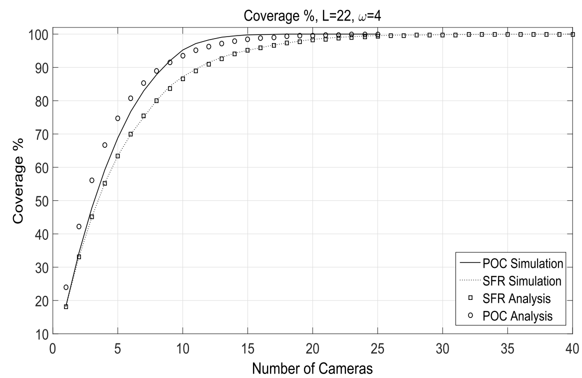

FIGURE 8. **Coverage percentage of POC and SFR based schemes versus number of cameras for $L = 22$ and $w = 4$.**

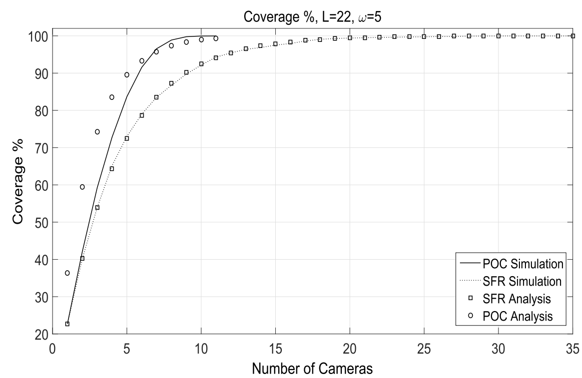

FIGURE 9. **Coverage percentage of POC and SFR based schemes versus number of cameras for $L = 22$ and $w = 5$.**

scheme outperforms the SFR-based scheme in coverage percentage, which is desirable. It can also be observed that the difference in coverage increases for the POC-based scheme as w and the number of cameras increase due to the efficiency of the activation distribution of the codewords. A slight difference emerges between the simulation and analytical results of the POC-based scheme when $w = 5$ and the number of cameras is small due to the approximations used in the analysis. When the number of cameras increases, the coverage probability of both the analytical model and the simulation become the same.

Figures 7, 8 and 9 give the coverage percentage versus the number of cameras for $L = 22$ and $w = 3$, 4,

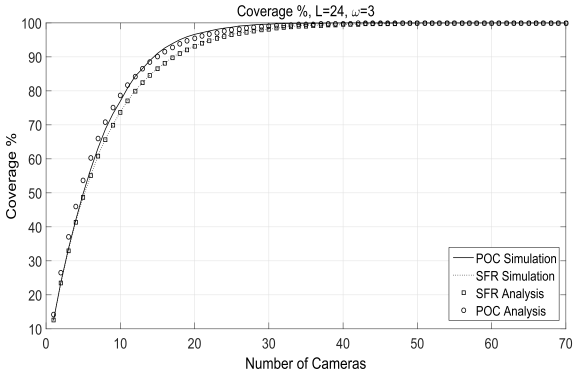

FIGURE 10. Coverage percentage of POC and SFR based schemes versus number of cameras for $L = 24$ and $w = 3$.

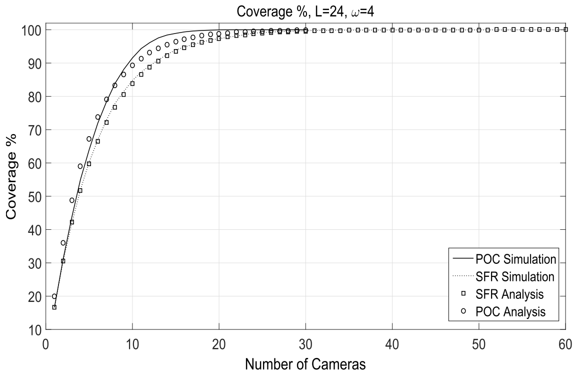

FIGURE 11. Coverage percentage of POC and SFR based schemes versus number of cameras for $L = 24$ and $w = 4$.

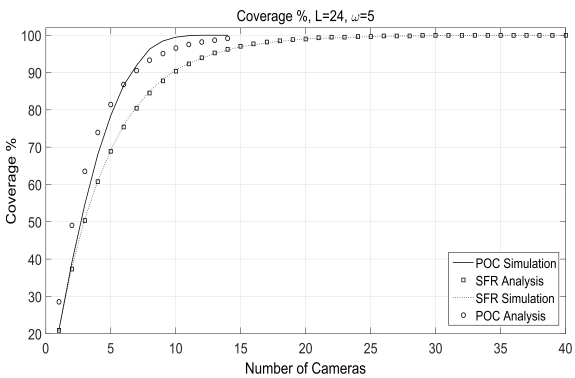

FIGURE 12. Coverage percentage of POC and SFR based schemes versus number of cameras for $L = 24$ and $w = 5$.

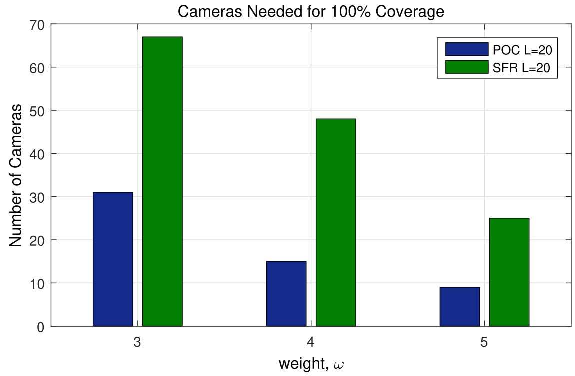

FIGURE 13. Number of cameras required for full coverage in POC and SFR based schemes for $L = 20$ and different values of w.

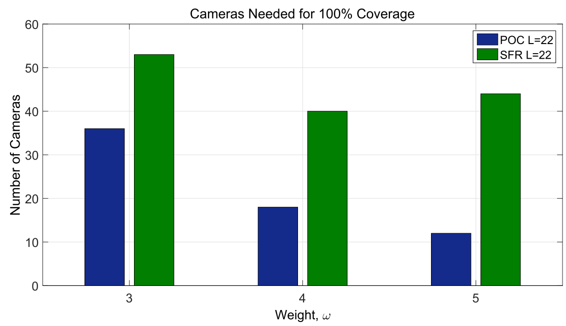

FIGURE 14. Number of cameras required for full coverage in POC and SFR based schemes for $L = 22$ and different values of w.

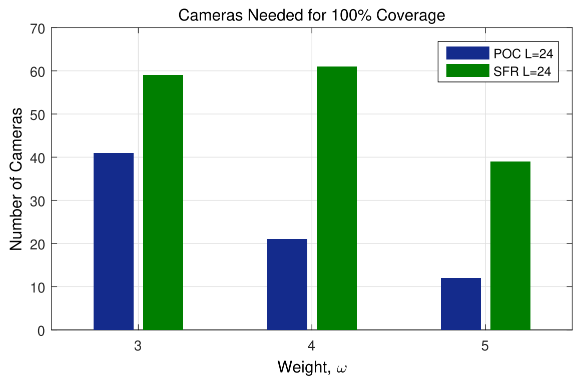

FIGURE 15. Number of cameras required for full coverage in POC and SFR based schemes for $L = 24$ and different values of w.

and 5, respectively. From the figures, it can be seen that the POC-based scheme clearly outperforms the SFR-based scheme in coverage percentage, which is desirable. The same conclusion can be observed in Figures 10, 11, and 12 when $L = 24$, except that the number of cameras required for 100% coverage generally increases due to the increase in number of time slots.

B. COST IN NUMBER OF CAMERAS NEEDED FOR FULL COVERAGE

In order to evaluate the cost of our system, the number of cameras needed for full coverage is measured. The coverage percentage per camera is calculated, as explained in the previous section, for all 200 versions and then the average of these 200 versions is computed to determine when 100% coverage can be achieved. This is a new metric that demonstrates the effectiveness and also the cost of the proposed scheme.

Figures 13, 14, and 15 give the number of cameras required to guarantee 100% coverage for the POC-based scheme and the SFR-based scheme, for $L = 20$, 22, and 24, respectively. In each figure, three values for w, including 3, 4, and 5 are considered.

Clearly, the figures show that the POC-based scheme requires a smaller number of cameras than the SFR-based scheme. The difference in the number of cameras depends on the values of L and w, and the number of cameras needed in case of SFR-based scheme can be more than twice the number of cameras required in the POC-based scheme. This can be attributed to the fact that in the SFR-based scheme, the activation codes make more redundant coverage cases (two or more cameras are active in the same time slot) than the POC-based scheme. This happens because the activation time slots are randomly selected in case of the SFR-based scheme, but the POC-based scheme makes sure that the codewords are cross-correlated. It can also be observed that fewer cameras are needed to achieve full coverage as the value of w increases. However, the downside of increasing w is that the system consumes more energy because the cameras are activated in more time slots.

VIII. CONCLUSION AND FUTURE WORK

The high demand for surveillance systems has motivated research efforts in this area. There is a need for WCSNs to provide solutions for large-scale environments with a full-coverage guarantee, low energy consumption, and improved communication QoS. The main contribution of this paper is the utilization of POCs, as they distribute activations efficiently over different time slots. As a result, they can provide full coverage with a small number of activations, thereby reducing energy consumption. In addition, POCs showed that they require significantly fewer cameras than the SFR-based scheme and *can cover the same areas with around half the number of cameras, which reduces costs*. The POC improves the communication QoS due to its independent decision-making nature and fault tolerance-distributed topology. In addition, the paper provides a theoretical study of the distributed coverage problem using POC, and presents a probabilistic analysis of the distributed coverage algorithm.

A study on the improved network performance and QoS can be conducted in the future. In addition, the system can be practically implemented and tested for real-life scenarios. The use of POC may be investigated in other fields in surveillance systems, such as multi-camera tracking scenarios or operating pan-tilt-zoom (PTZ) cameras. The POC showed good results regarding efficiency in activation distribution, which indicates that it can be applied in situations where fairness is required. Some examples include the Internet of Things and smart cities, where the number of sensor activations is meant to be reduced while the QoS is achieved.

Moreover, several challenges emerged in this work, including the generation of POC codes. Code generation requires a long processing time. However, once the codes are generated, they can be stored in a lookup table. Fortunately, our system does not require the continuous generation of codes. However, an investigation into fast and optimal algorithms will definitely be an asset to other applications.

Finally, in order to analyze the proposed system, different values for L and w have been used. We selected L which is a system parameter and then our scheme computes codewords using w in a distributed way (without exchanging messages) that can reduce the number of active cameras needed to cover the target areas. Investigating optimum values for L and w is an interesting problem that will be investigated in our future work.

REFERENCES

[1] A. Hampapur, L. Brown, J. Connell, S. Pankanti, A. Senior, and Y. Tian, "Smart surveillance: Applications, technologies and implications," in *Proc. 4th Int. Conf. Inf., Commun. Signal Process., 4th Pacific Rim Conf. Multimedia*, vol. 2, Dec. 2003, pp. 1133–1138.

[2] X. Huan, K. Lin, W. Chaowei, L. Xiuhua, and Z. Yinghai, "Minimal coverage set detecting algorithm for barrier coverage in wireless sensor networks," in *Proc. 4th IEEE Int. Conf. Netw. Infrastruct. Digit. Content*, Sep. 2014, pp. 278–282.

[3] V. S. Asirvadam, C. P. Fen, N. Saad, P. Sebastian, A. A. Altahir, A. Ali, and N. H. Hamid, "Risk map for video surveillance CCTV," in *Proc. 5th Int. Conf. Intell. Adv. Syst. (ICIAS)*, Jun. 2014, pp. 1–6.

[4] T.-Y. Lin, H. A. Santoso, and K.-R. Wu, "Global sensor deployment and local coverage-aware recovery schemes for smart environments," *IEEE Trans. Mobile Comput.*, vol. 14, no. 7, pp. 1382–1396, Jul. 2015.

[5] X. Ren, W. Liang, and W. Xu, "Quality-aware target coverage in energy harvesting sensor networks," *IEEE Trans. Emerg. Topics Comput.*, vol. 3, no. 1, pp. 8–21, Mar. 2015.

[6] E. Yildiz, K. Akkaya, E. Sisikoglu, and M. Y. Sir, "Optimal camera placement for providing angular coverage in wireless video sensor networks," *IEEE Trans. Comput.*, vol. 63, no. 7, pp. 1812–1825, Jul. 2014.

[7] H. Huang, C.-C. Ni, X. Ban, J. Gao, A. T. Schneider, and S. Lin, "Connected wireless camera network deployment with visibility coverage," in *Proc. IEEE Conf. Comput. Commun. (INFOCOM)*, Apr. 2014, pp. 1204–1212.

[8] J. Du, K. Wang, H. Liu, and D. Guo, "Maximizing the lifetime of K-discrete barrier coverage using mobile sensors," *IEEE Sensors J.*, vol. 13, no. 12, pp. 4690–4701, Dec. 2013.

[9] Q. Wang, J. Wu, and C. Long, "On-line configuration of large scale surveillance networks using mobile smart camera," in *Proc. 7th Int. Conf. Distrib. Smart Cameras (ICDSC)*, Oct. 2013, pp. 1–6.

[10] B. Wang, "Coverage problems in sensor networks: A survey," *ACM Comput. Surv.*, vol. 43, no. 4, pp. 1–53, 2011.

[11] S. Meguerdichian, F. Koushanfar, M. Potkonjak, and M. B. Srivastava, "Coverage problems in wireless ad-hoc sensor networks," in *Proc. IEEE INFOCOM Conf. Comput. Commun. 20th Annu. Joint Conf. IEEE Comput. Commun. Soc.*, vol. 3, Apr. 2001, pp. 1380–1387.

[12] M. Younis and K. Akkaya, "Strategies and techniques for node placement in wireless sensor networks: A survey," *Ad Hoc Netw.*, vol. 6, no. 4, pp. 621–655, Jun. 2008.

[13] Y. Gu, Y. Ji, J. Li, and B. Zhao, "Covering targets in sensor networks: From time domain to space domain," *IEEE Trans. Parallel Distrib. Syst.*, vol. 23, no. 9, pp. 1643–1656, Sep. 2012.

[14] C. Liu and G. Cao, "Spatial-temporal coverage optimization in wireless sensor networks," *IEEE Trans. Mobile Comput.*, vol. 10, no. 4, pp. 465–478, Apr. 2011.

[15] Y. Mao, X. Li, and L. Chen, "Energy-efficient area coverage in heterogeneous energy wireless sensor networks," in *Proc. 4th Int. Conf. Wireless Commun., Netw. Mobile Comput.*, Oct. 2008, pp. 1–4.

[16] J. Wang, S. Medidi, and M. Medidi, "Energy-efficient K-Coverage for wireless sensor networks with variable sensing radii," in *Proc. IEEE Global Telecommun. Conf. (GLOBECOM)*, Nov. 2009, pp. 1–6.

[17] Z. Lu and W. W. Li, "Approximation algorithms for maximum target coverage in directional sensor networks," in *Proc. 11th IEEE Int. Conf. Netw., Sens. Control*, Apr. 2014, pp. 155–160.

[18] J. Jia, C. Dong, Y. Hong, L. Guo, and Y. Yu, "Maximizing full-view target coverage in camera sensor networks," *Ad Hoc Netw.*, vol. 94, Nov. 2019, Art. no. 101973.

[19] D.-R. Chen, L.-C. Chen, M.-Y. Chen, and M.-Y. Hsu, "A coverage-aware and energy-efficient protocol for the distributed wireless sensor networks," *Comput. Commun.*, vol. 137, pp. 15–31, Mar. 2019.

[20] C. Liu and G. Cao, "Distributed critical location coverage in wireless sensor networks with lifetime constraint," in *Proc. IEEE INFOCOM*, Mar. 2012, pp. 1314–1322.

[21] S. S. Dhillon and K. Chakrabarty, "Sensor placement for effective coverage and surveillance in distributed sensor networks," in *Proc. IEEE Wireless Commun. Netw. (WCNC)*, Mar. 2003, pp. 1609–1614.

[22] N. Shrestha, J.-H. Youn, and N. Sharma, "A code-based sleep and wakeup scheduling protocol for low duty cycle sensor networks," in *Proc. Int. Conf. Netw. Inf. Technol.*, Jun. 2010, pp. 80–85.

[23] F. Farnoud Hassanzadeh and S. Valaee, "Reliable broadcast of safety messages in vehicular ad hoc networks," in *Proc. IEEE 28th Conf. Comput. Commun. (INFOCOM)*, Apr. 2009, pp. 226–234.

[24] F. Farnoud and S. Valaee, "Repetition-based broadcast in vehicular ad hoc networks in Rician channel with capture," in *Proc. IEEE Conf. Comput. Commun. Workshops (INFOCOM)*, Apr. 2008, pp. 1–6.

[25] F. Farnoud, B. Hassanabadi, and S. Valaee, "Message broadcast using optical orthogonal codes in vehicular communication systems," in *Proc. 1st Int. Workshop Wireless Netw. Intell. Transp. Syst. (WINITS)*, 2007, pp. 1–6.

[26] B. Hassanabadi, L. Zhang, and S. Valaee, "Index coded repetition-based MAC in vehicular ad-hoc networks," in *Proc. IEEE Consum. Commun. Netw. Conf.*, Jan. 2009.

[27] A. Honarvar and S. Valaee, "Selection of repetition codes for MAC in vehicular ad hoc networks," in *Proc. IEEE Wireless Commun. Netw. Conf.*, Apr. 2010, pp. 1–6.

[28] B. Hassanabadi and S. Valaee, "Reliable network coded MAC in vehicular ad-hoc networks," in *Proc. IEEE 72nd Veh. Technol. Conf. (Fall)*, Sep. 2010, pp. 1–5.

[29] B. Hassanabadi and S. Valaee, "Reliable periodic safety message broadcasting in VANETs using network coding," *IEEE Trans. Wireless Commun.*, vol. 13, no. 3, pp. 1284–1297, Mar. 2014.

[30] L. Zhang, B. Hassanabadi, and S. Valaee, "Cooperative forwarding for vehicular networks using positive orthogonal codes," in *Proc. IEEE 24th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Sep. 2013, pp. 1935–1940.

[31] S. Johnson, "A new upper bound for error-correcting codes," *IEEE Trans. Inf. Theory*, vol. 8, no. 3, pp. 203–207, Apr. 1962.

[32] Q. Xu, T. Mak, J. Ko, and R. Sengupta, "Medium access control protocol design for vehicle–vehicle safety messages," *IEEE Trans. Veh. Technol.*, vol. 56, no. 2, pp. 499–518, Mar. 2007.

[33] Y.-K. Wang, C.-T. Fan, and C.-R. Huang, "A large scale video surveillance system with heterogeneous information fusion and visualization for wide area monitoring," in *Proc. 8th Int. Conf. Intell. Inf. Hiding Multimedia Signal Process.*, Jul. 2012, pp. 178–181.

[34] L. Zhang, "Positive orthogonal code-based cooperative forwarding for VANETs," M.S. thesis, Dept. Elect. Comput. Eng., Univ. Toronto, Toronto, ON, Canada, 2009.

[35] F. R. K. Chung, J. A. Salehi, and V. K. Wei, "Optical orthogonal codes: Design, analysis and applications," *IEEE Trans. Inf. Theory*, vol. 35, no. 3, pp. 595–604, May 1989.

MAAZEN ALSABAAN received the B.S. degree in electrical engineering from King Saud University (KSU), Saudi Arabia, in 2004, and the M.A.Sc. and Ph.D. degrees in electrical and computer engineering from the University of Waterloo, Canada, in 2007 and 2013, respectively. He is currently an Assistant Professor with the Department of Computer Engineering, King Saud University, where he was the Chairman of the department, from 2015 to 2018. He serves as a Consultant for different agencies and has been awarded many grants from KSU and King Abdulaziz City for Science and Technology (KACST). His current research interests include wireless communications and networking, surveillance systems, vehicular networks, green communications, intelligent transportation systems, and cybersecurity.

WALEED ALSMARY (Senior Member, IEEE) received the B.Sc. degree (Hons.) in computer engineering from Umm Al-Qura University, Saudi Arabia, in 2005, the M.A.Sc. degree in electrical and computer engineering from the University of Waterloo, Canada, in 2010, and the Ph.D. degree in electrical and computer engineering from the University of Toronto, Toronto, Canada, in 2015. During his Ph.D. studies, he was a Visiting Research Scholar with the Network Research Laboratory, UCLA, in 2014. He was a Fulbright Visiting Scholar with the CSAIL Laboratory, MIT, from 2016 to 2017. Subsequently, he joined the College of Computer and Information Systems, Umm Al-Qura University, as an Assistant Professor of Computer Engineering, where he is currently an Associate Professor. His "Mobility impact on the IEEE 802.11p" article is among the most cited *Ad Hoc Networks* journal articles list in 2016–2018. His current research interests include mobile computing, ubiquitous sensing, intelligent transportation systems, and privacy and anonymity.

ABDULAZIZ ALQUNIAH is currently a Researcher in the field of Wireless Communication and Networking.

MOHAMED MAHMOUD (Senior Member, IEEE) received the Ph.D. degree from the University of Waterloo, in April 2011. From May 2011 to May 2012, he worked as a Postdoctoral Fellow with the Broadband Communications Research Group, University of Waterloo. From August 2012 to July 2013, he was a Visiting Scholar with the University of Waterloo and a Postdoctoral Fellow with Ryerson University. He is currently an Associate Professor with the Department of Electrical and Computer Engineering, Tennessee Tech University, USA. He is the author of more than 23 papers published in major IEEE conferences and journals, such as the INFOCOM conference and IEEE Transactions on Vehicular Technology, IEEE Transactions on Mobile Computing, and IEEE Transactions on Parallel and Distributed Systems. His research interests include security- and privacy-preserving schemes for smart grid communication networks, mobile ad hoc networks, sensor networks, and delay-tolerant networks. He received the NSERC-PDF Award. He won the Best Paper Award from IEEE International Conference on Communications (ICC'09), Dresden, Germany, in 2009. He serves as an Associate Editor for *Peer-to-Peer Networking and Applications* (Springer). He served as a technical program committee member for several IEEE conferences and as a reviewer for several journals and conferences, such as IEEE Transactions on Vehicular Technology, IEEE Transactions on Parallel and Distributed Systems, and the journal *Peer-to-Peer Networking and Applications*.

MAHMOUD NABIL received the B.S. and M.S. degrees in computer engineering from Cairo University, Cairo, Egypt, in 2012 and 2016, respectively, and the Ph.D. degree from Tennessee Tech University, USA, in 2019. He is currently an Assistant Professor with the Department of Electrical and Computer Engineering, North Carolina A&T University, USA. His research interests include machine learning, cryptography and network security, smart grid and AMI networks, and vehicular ad hoc networks.