Autonomous Channel Switching: Towards Efficient Spectrum Sharing for Industrial Wireless Sensor Networks

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Abstract—Industrial wireless sensor networks (IWSNs) are committed to bring the industry automation into the era of Industry 4.0 by providing the ubiquitous perception to improve the production efficiency. However, the proliferation of wireless devices in industrial applications makes the spectrum sharing in limited ISM (Industrial, Scientific, and Medical) band a challenging problem. In this paper, it is concerned with the intrinsic impact of the evenness of spectrum usage on the spectrum sharing performance in terms of channel accessing probability, spectrum utilization, and fairness of spectrum usage. In order to explore the explicit relationship between the evenness and spectrum sharing performance, a new concept of equilibrium is first defined to represent the achievable best evenness of spectrum usage. Then, a set of rules called Local EQuilibrium guided Autonomous Channel Switching (LEQ-AutoCS) are devised, with which each accessed sensor autonomously equalizes the local channel occupations within its range of spectrum sensing without overhead on exchanging the sensors’ spectrum sensing reports. It is further proved that the equilibrium can be achieved by this concessive manner. Theoretical analysis and experiments results demonstrate that the proposed LEQ-AutoCS rules provide higher utilization and fairness of spectrum usage comparing to the existing spectrum access approaches. Moreover, it is shown that LEQ-AutoCS rules assist the system to reduce the spectrum access delay to 1/2 of CSMA based systems and 1/50 of TDMA based systems, respectively.

Index Terms—Industrial wireless sensor networks, spectrum sharing, autonomous channel switching, equilibrium

I. INTRODUCTION

The development of wireless sensor networks in the last decades is bringing the Internet of Things (IoT) to the world, which promotes the industry automation entering the era of Industry 4.0. Industrial wireless sensor networks (IWSNs), as the fundamental element for the realization of IoT in industry, are endowed with the advantages in terms of rapid deployment, low-cost maintaining, flexibility, and scalability [1, 2]. They are taken as one of the most promising techniques for Industry 4.0 to ubiquitously perceive the industrial processes [3]. Recent applications in industry witness the improvement of productivity and efficiency by using IWSNs [4, 5]. Taking the hot strip mill of Bao Steel, Shanghai, China shown in Fig. 1 as an example, hundreds of sensors are deployed to monitor different milling processes including reversing roughers R1 and R2, finishing mill, laminar cooling, and down coiler. In order to guarantee the quality of alloy steel, hundreds of sensors can be deployed to monitor the milling process to perceive the strip temperature, thickness, milling pressure, and other process data to acquire the precise mathematic model and improve the precision of process control [6]. IWSNs can also provide a dedicated temperature evolution monitoring to support flexible milling [7]. For the general application of equipment health monitoring, IWSNs can work continuously to reduce the unexpected downtime. It is foreseeable that in the very near future IWSNs would become a standard feature of smart factory in the era of Industry 4.0.

However, the ever-increasing wireless communication demands necessitate efficient spectrum sharing strategies to improve spectrum efficiency of IWSN in limited ISM band. The existing standardized industrial wireless protocols, such as WirelessHART [8], ISA100.11a [9], and WIA-PA [10], implement the spectrum sharing based on the superframe design. The slotted channels are periodically allocated to the wireless sensors for data packet delivery, which are efficient for the periodic data gathering in small-scale networks. To provide efficient spectrum sharing for event-driven data collection in large-scale networks, more flexible and powerful spectrum sharing strategies are expected. Recently, many works have been done for the efficient spectrum sharing, such as cooperative spectrum sharing to increase the spectrum utilization [11, 12], or game theory based methods to improve the fairness of spectrum sharing [13, 14]. However, all these methods inevitably require frequent exchange of the spectrum sensing reports among entities to obtain a convergence result. For practical applications, they would cost considerable network resource (including spectrum resource and time), which is not acceptable in IWSNs due to strict timeliness requirement. Contention based spectrum access is an effective way for small-scale IWSNs, which provides fast spectrum access. However, for large-scale networks, without global knowledge of spectrum states and efficient coordination, the channels cannot be fairly used which may lead to the congestion on some certain channels while some others are relatively vacant. It has
been demonstrated that contention based spectrum access in large-scale networks results in long spectrum accessing delay and low network throughput [15, 16].

This paper aims to develop a simple but effective way to improve the spectrum sharing by the inspiration from the collective behaviors in biological systems [17], such as line forming of the flying geese and vortices forming of the fish school. In the collective biological system, when one agent joins or leaves the formation, each agent in the system will autonomously adapt its behavior (such as adjustment of position, direction, and speed) according to the local observation of neighbor agents’ states, and thus the system motion sustains the consensus. Based on this observation, a concession based spectrum sharing scheme is proposed to approach the collective spectrum usage by sensors’ autonomous channel switching. Specifically, the concept of equilibrium of spectrum occupation is defined to show the best evenness of spectrum usage. A set of rules named Local EQuilibrium guided Autonomoum Channel Switching (LEQ-AutoCS) are devised, with which each accessed sensor switches the channel autonomously based on the self-observation on limited spectrum range, thus to achieve the evenness of channel usage within this spectrum range. We have preliminarily studied the autonomous channel switching to improve the evenness of spectrum usage in [18]. In this work, we design the specific consoles for accessed sensors to conduct autonomous channel switching. The convergence of the equilibrium of the whole spectrum usage based on the proposed spectrum sharing scheme is proved. Finally, the improvement of utilization and fairness of spectrum usage are evaluated by simulations and experiments based on universal software radio peripheral (USRP) and PCI extensions for instrumentation (PXI) platform. We summarize the main contributions of this paper as follows:

- First, inspired by the collective motion, we investigate that an evener spectrum usage facilitates to improve the spectrum sharing performance in IWSNs, such as spectrum access delay, utilization and fairness of spectrum usage.
- Then, a new concept of equilibrium is defined to represent the achievable best evenness of spectrum usage. A set of rules called LEQ-AutoCS are devised for accessed sensors to approach the equilibrium by autonomous channel switching based on local sensing results, which avoid the exchange of spectrum sensing reports.
- Finally, both theoretical and experimental results validate that with LEQ-AutoCS rules, the equilibrium of spectrum usage is always achievable and thus the spectrum sharing performance criteria above are improved.

The remainder of this paper is organized as follows. Section II gives a brief review on existing works. Section III presents the network model and performance criteria of spectrum utilization. In Section IV, the so-called LEQ-AutoCS rules are proposed. Theoretical analysis on the network performance based on the proposed rules is presented in Section V. In Section VI, numerical and experiment results are presented. Conclusion and future works are given in Section VII.

II. RELATED WORKS

As the proliferation of wireless sensor networks in industrial applications, three standardized protocols have been developed for efficient coordination of IWSNs, i.e., WirelessHART [8], ISA100.11a [9], and WIA-PA [10]. Based on IEEE 802.15.4 standard, the existing standardized protocols implement the spectrum sharing by the design of superframe. In the superframe, the slotted channels are allocated to network devices in reservation manner. Then the network devices transmit or receive the data packets under the superframe repeatedly. For example, the superframe scheduler in WirelessHART protocol allocates the guaranteed time slots (GTS) to network devices. The protocol of ISA100.11a introduces the slotted channel hopping mechanism to enhance the communication robustness in the interfered radio environment. Similar spectrum sharing mechanism is used in WIA-PA. In order to improve the transmission reliability, redundant transmission scheme is executed to the reservation based scheduling, which can decrease the spectrum utilization. In addition, to adapt to the network dynamics (e.g., spectrum dynamics and data traffic dynamics), the superframe scheduler has to update the superframe design frequently. It is time-consuming for large-scale IWSNs. Motivated by the strong demand and tremendous trend of industrial wireless networking, how to enable the high spectrum utilization in a scalable and cost-effective manner is therefore a key research issue for the development of IWSN.

In order to adapt to spectrum dynamics and improve the spectrum sharing efficiency, many distributed spectrum sharing approaches have been proposed, either in the contention based manner or the cooperative manner. In [19, 20], different carrier sense multiple access (CSMA) based opportunistic spectrum sharing schemes are devised using the round-robin or random spectrum sensing and access approach. However, the authors...
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in [15, 16] have proved that for large-scale network, the CSMA based channel access would bring in seriously collision among the new spectrum access requests, which results in low transmission probability. As a result, the performances in terms of spectrum access delay, network throughput and spectrum utilization are all low.

The cooperative manner is considered to be more efficient for spectrum sharing since different network utilities can be achieved by the cooperation. The spectrum utilization of network and the fairness of sensors’ resource allocation are considered in [11, 12, 14]. The authors in [21–23] considered the fair spectrum sharing with varying traffic of sensors. In [13], a distributed game based channel allocation algorithm is proposed for spectrum sharing, which leads negotiations among the sensors and finally reaches to a Nash Equilibrium. The authors in [24, 25] propose a flexible and fast channel access scheme based on multi-agent imitation in mobile WSN. In [26], a biologically-inspired spectrum sharing algorithm is adopted to model the local cooperative spectrum sensing for wireless sensor networks to facilitate the dynamic resource allocation, and a swarming mechanism is devised for collision avoidance and spatial reuse of spectrum resource. However, this spectrum sharing algorithm requires that each sensor has the knowledge of neighboring sensors’ observation on channel states. All the aforementioned distributed cooperative algorithms require sensors to exchange spectrum sensing reports iteratively till a consensus is achieved. By using these algorithms, the exchange of spectrum sensing reports among the sensors occupies considerable spectrum and time resource, which inevitably decreases the spectrum efficiency. Moreover, the iteration process is also time-consuming, which may result in long access delay and thus is not applicable for the timeliness requirement in industrial applications.

Therefore, for large-scale IWSNs, a good spectrum sharing method should promote the spectrum utilization, improve the fairness of spectrum usage, decrease the spectrum access delay, and also be easy to implement with low overhead.

### III. IWSN Model and Problem Formulation

In this work, we select the hot strip mill process monitoring in BaoSteel, Shanghai, China as our application scenario. As shown in Fig. 1, the rolling process consists of several process sections, such as reversing roughers, finishing mill, laminar cooling, and down coiler. We design a three-layer network as shown in Fig. 2 to cater to the hot rolling production line. Specifically, the plant network is in charge of the configuration and management of production. The control network is responsible for the process control with the monitoring data from field network. In the field network, a large amount of sensors are deployed to perceive the production process and transmit the reports to the upper layers. As multiple process sections of the production line are naturally laid out one by one in the plant, we group the sensors around one section into a clustered subnetwork named FieldNet as shown in Fig. 2. For each FieldNet, one access point (AP) is employed to collect the data packets from the sensors. In this paper, we focus on the spectrum sharing problem of the FieldNet.

#### A. Network model

Suppose that the FieldNet is time slotted and synchronized. The spectrum is divided into $M$ non-overlapping orthogonal channels with equal bandwidth, i.e., $\{C_m\}, m = 1, 2, \ldots, M$ with the order from the lowest frequency channel to the highest one. Without ambiguity, let $C_m(t) = 0$ represent the idle state and $C_m(t) = 1$ represent the occupied state at the slot $t$, respectively. The symbol $t$ is omitted for simplicity for the analysis within one slot in the following. The AP is with multiple interfaces which covers the channels assigned to the network.

The sensors transmit data over single channel but can sense a number of consecutive channels. Without loss of generality, we assume that each sensor can simultaneously sense three consecutive channels. It is noted that the method to be proposed is easy to be extended to the scenarios of different sensing ranges. Here, each sensor always aligns the radio central frequency to the transmission channel’s central frequency. Hence, one sensor transmitting on channel $C_m$ can sense the states of channels $\{C_{m-1}, C_m, C_{m+1}\}$. If it switches its transmission channel to $C_{m+1}$, its sensing channels become $\{C_m, C_{m+1}, C_{m+2}\}$.

Sensors work on event-driven manner. If one sensor has data to transmit, it enters to the accessing state to wait and seek one idle channel for transmission. After it has successfully accessed a channel, it switches to the accessed state. At the accessed state, the sensor also will sense the local spectrum and can switch channel according to some proper rules which are to be determined in this paper.

#### B. Performance criteria

Compared to other applications of wireless sensor networks, IWSNs have higher requirements in terms of network throughput, channel access delay, network scalability, etc [1, 2]. However, the limited radio spectrum resource in industry fields makes the IWSNs more challenging to improve the network efficiency and transmission performance.
performance while wireless devices are boosting. Therefore, the spectrum sharing scheme in IWSNs vitally concerns the network performance. In this work, we investigate that an evener spectrum usage normally facilitates the traffic load balance over the channels and avoids the local congestion of spectrum access, thus decreases the channel access delay and improves the utilization and fairness of spectrum usage. We aim to increase the spectrum sharing efficiency by improving the evenness of spectrum usage. Hence, the following three criteria are considered, i.e., spectrum access probability of accessing sensors, spectrum utilization, and fairness, where a higher spectrum access probability means faster spectrum accessing sensors, spectrum utilization, and fairness, where the evenness of spectrum usage. Hence, the following three criteria are considered, i.e., spectrum access probability of accessing sensors, spectrum utilization, and fairness, where a higher spectrum access probability means faster spectrum access for accessing sensors.

Assume that an accessing sensor randomly set a central channel \( C_m \) \( (2 \leq m \leq M - 1) \) with probability \( \frac{1}{M-2} \), and scans the spectrum range \( \{ C_{m-1}, C_m, C_{m+1} \} \). Obviously, the accessing sensor will successfully access a channel only if not all the three channels’ states are equal to 1. Therefore, the spectrum access probability \( P_a \) for the accessing sensor is defined as

\[
P_a \triangleq 1 - \frac{1}{M-2} \sum_{m=2}^{M-1} C_{m-1} C_m C_{m+1}. \tag{1}
\]

We quantify the utilization and fairness of spectrum usage from the viewpoint of statistics over \( T \) time slots. First, we define the channel utilization of \( C_m \) as the ratio of occupation time over \( T \) time slots, i.e.,

\[
U_m \triangleq \frac{1}{T} \sum_{t=1}^{T} C_m(t), m = 1, 2, \ldots, M. \tag{2}
\]

Then, the system utilization of the all channels is

\[
U \triangleq \frac{1}{M} \sum_{m=1}^{M} U_m. \tag{3}
\]

To evaluate the fairness of channels’ usage, the Jain’s fairness [27] is exploited:

\[
U_f \triangleq \frac{(\sum_{m=1}^{M} U_m)^2}{M \sum_{m=1}^{M} U_m^2}. \tag{4}
\]

This metric identifies underutilized channels. Note that the result of Jain’s fairness ranges from \( \frac{1}{M} \) (worst fairness) to 1 (best fairness). When only one channel is used, it results the worst fairness, and when the channels are used equally, it achieves best fairness.

The objective of this paper is to explore the explicit relationship between the evenness of spectrum usage and the spectrum sharing performances mentioned above, and further to propose the autonomous channel switching rules to achieve the evenness of spectrum usage.

IV. LOCAL EQUILIBRIUM GUIDED AUTONOMOUS CHANNEL SWITCHING RULES (LEQ-AutoCS)

In this section, the details of LEQ-AutoCS rules are presented. Note that the collective motion in biological systems can be achieved by agents’ autonomous actions with local information. In such systems, each collective individual in the system autonomously adjusts its own dynamics to coordinate itself with the neighbors within its scope of observation and avoids collisions with them. In this way, the whole system exhibits a dynamic formation. Reconsidering the spectrum sharing problem from the perspective of collective motion, we regard the accessed sensors as agents and the desired collective motion as the optimal evenness of channels’ occupation. When the collective motion reaches the optimum, the occupied channels are evenly distributed in the given spectrum range. Considering discretely channelized spectrum and channel sensing model, we give a definition of equilibrium to demonstrate the optimal evenness of spectrum usage in the following.

**Definition 1 (Equilibrium):** Suppose that \( N \) of \( M \) channels are occupied by the sensors. The equilibrium of spectrum usage is defined as the state which satisfies any of the following two conditions:

1) for \( N \leq \lfloor M/2 \rfloor \), there do not exist any two neighboring occupied channels, or

2) for \( N > \lfloor M/2 \rfloor \), there do not exist any two neighboring free channels and both \( C_1 \) and \( C_M \) are occupied.

**Remark 1:** The equilibrium may not be unique. It represents the state with optimal evenness of spectrum usage. For example, when \( M = 7 \) and \( N = 4 \), the equilibrium of spectrum usage is unique, i.e., \( \{1, 0, 1, 0, 1, 0, 1\} \). But when \( N = 5 \), there are more than one channel occupation states achieving the equilibrium, such as \( \{1, 1, 1, 0, 1, 0, 1\} \) and \( \{1, 0, 0, 0, 0, 0, 1\} \) according to Definition 1.

According to the definition of equilibrium, we concern the spectrum usage of individual sensors within its sensing range (three channels), and present the definition of local equilibrium of spectrum usage as follows.

**Definition 2 (Local equilibrium):** Within the sensing range \( \{ C_{m-1}, C_m, C_{m+1} \} \), we have the following statement: 1) if no more than one channel is occupied, any occupation state is the local equilibrium; 2) if two channels are occupied, the local equilibrium is unique, i.e., \( \{1, 0, 1\} \); 3) if all the three channels are occupied, i.e., \( \{1, 1, 1\} \), the local equilibrium is also achieved.

The key point of autonomous switching rules is to enable each sensor to achieve the local equilibrium of spectrum usage, thus to achieve the equilibrium of the whole spectrum range. In the following, we aim to propose a concession based spectrum sharing scheme for the accessed sensors to switch channels autonomously. We first define three consoles, and then present the so-called LEQ-AutoCS rules.

1) **Potential Indicator.** The concept of potential is borrowed from collective motion in biological systems [17]. It describes the relationship between the accessed sensor \( s_m \) using channel \( C_m \) and its neighboring sensors in the sensing frequency range. Specifically,

\[
E_{m}^t \triangleq \begin{cases} 
0, & C_{m-1} = 0, \\
1, & C_{m-1} = 1,
\end{cases} \tag{5}
\]

\[
E_{m}^r \triangleq \begin{cases} 
0, & C_{m+1} = 0, \\
-1, & C_{m+1} = 1,
\end{cases} \tag{6}
\]

\[
E_{m}^w \triangleq E_{m}^t + E_{m}^r. \tag{7}
\]
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where $E^t_m$ represents the potential from the neighboring sensor at lower channel $C_{m-1}$ to the sensor $s_n$ at $C_m$, which propels the sensor $s_n$ to switch to the channel $C_{m+1}$. $E^t_m$ has the similar effect but with opposite direction from $C_{m+1}$ to $C_m$. Specially, define $E^t_1 = 0$ and $E^t_M = 0$. $E^t_m$ represents the aggregated potential of sensor $s_n$.

2) Time Regulator. This console is to avoid the collisions which may be caused by both accessing and accessed sensors trying to access the same channel simultaneously. As shown in Fig. 3, a time fraction at the beginning of each slot is set to regulate the sensors’ actions, which is divided into three sub-slots with equal length $t_s$, $0 < t_s < 1$. The accessing sensor accesses channel and accessed sensor departs from channel within $(t, t + t_s)$. The accessed sensor switches to higher neighboring channel within $(t + t_s, t + 2t_s)$. The accessed sensor switches to lower neighboring channel within $(t + 2t_s, t + 3t_s)$. This time regulator not only grants the priority to accessing sensors for acquiring the free channels, but also guarantees that there are no collisions among the accessing and accessed sensors.

3) Switching Controller. This console is to control the pace of channel switching and prevent sensors from ping-pong switching. Let $v_m = 0$ represent the case that $s_n$ on channel $C_m$ did not switch at the last time slot, and $v_m = 1$ represent the case it switched from other channel at the last slot. For $v_m = 1$, the accessed sensor $s_n$ on channel $C_m$ is not permitted to switch channel at this slot.

Based on the three consoles, each accessed sensor is allowed to adjust the transmission channel according to the sensing result and equalize the distribution of channels usage among its sensing range, to reach the local equilibrium of spectrum usage. The LEQ-AutoCS rules are given as follows:

**LEQ-AutoCS rules:**

**Rule I:** In sub-slot $(t + t_s, t + 2t_s)$,

a) If $E^t_m = 0$ or $v_m = 0$, the sensor $s_n$ keeps on the incumbent channel $C_m$ and set $v_m = 0$,
b) If $E^t_m = 1$ and $v_m = 0$, the sensor $s_n$ switches to the channel $C_{m+1}$ and set $v_m = 1$,

**Rule II:** In sub-slot $(t + 2t_s, t + 3t_s)$,

a) If $E^t_m = 0$ or $v_m = 1$, the sensor $s_n$ keeps on the incumbent channel $C_m$ and set $v_m = 0$,
b) If $E^t_m = 1$ and $v_m = 0$, the sensor $s_n$ switches to the channel $C_{m+1}$ and set $v_m = 1$.

**Rule III:** The sensor using channel $C_1$ or $C_M$ does not switch at all circumstances.

For the case of $E^t_m = 0$, both of the neighboring channels of $C_m$ are free or occupied simultaneously, which is at the equilibrium state according to Definition 2. The accessed sensor $s_n$ keeps on the incumbent channel in this case. For the cases of $E^t_m = 1$ or $E^t_m = -1$, local equilibrium of spectrum usage has not been achieved, and the accessed sensor $s_n$ is regulated to switch channel to reach the local equilibrium with the channels’ states of $\{1, 0, 1\}$. Fig. 4 presents a simple illustration for rules of autonomous channel switching, where Case I and Case II in Fig. 4 correspond to I.b) and II.b) in the LEQ-AutoCS rules, respectively.

It is worth noting that the rules can be extended to scenarios of different sensing ranges by set time regulator with different sub-slots to coordinate the sensors’ channel access and switching.

V. PERFORMANCE ANALYSIS

In this section, the convergence of spectrum usage is discussed and the performance of spectrum sharing is analyzed by the queueing network model.

A. Convergence of the collective channel occupations under the LEQ-AutoCS rules

We assume that $N$ sensors are initially randomly distributed over $M$ channels at the beginning, and there are no new accessing requests or departures. In the following, we show how LEQ-AutoCS rules facilitate to achieve the equilibrium of spectrum usage. First, we introduce the concept of absolute potential, which describes the potential on the systemic level.

**Definition 3 (Absolute Potential):** For the accessed sensor $s_n$ at the channel $C_m$, its absolute potential is defined as

$$E_m \triangleq \begin{cases} |E^t_m| + |E^r_m|, & C_m = 1, \\ 0, & C_m = 0, \end{cases}$$

and the absolute potential of the network system is defined as

$$E_{sys} = \sum_{m=1}^{M} E_m.$$  \hfill (9)

Then, we can obtain the following important properties.
When the system is at the equilibrium state. It is easy to obtain $E_{sys} = 0$ if $N \leq \lceil M/2 \rceil$, and $E_{sys} = 4N - 2M - 2$ if $N > \lceil M/2 \rceil$.

Forth, we analyze $P_a$ at the equilibrium state from the following two cases. 1) For $N \leq \lceil M/2 \rceil$, the equilibrium implies that any two neighboring channels will not be occupied simultaneously in the system. Thus, we have $C_{m-1} C_m C_{m+1} = 0, \forall 2 \leq m \leq M - 1$, which indicates that the accessing sensor can find at least one free channel in its sensing range with probability 1. 2) For $N > \lceil M/2 \rceil$, the equilibrium implies that there are not any two neighboring free channels and $\{C_1, C_M\}$ are occupied. As $N$ channels are occupied, there are $(M - N)$ free channels. In the following, we analyze the worst and best cases for $P_a$, respectively. a) When there is only one occupied channel between any two adjacent free channels, the $P_a$ for accessing sensor is minimum, which is $P_a = \frac{2(M-N)}{M-2}$. b) When there are more than one occupied channel between any two adjacent free channels, the spectrum access probability for new accessing sensor is the maximum, $P_a = \frac{3(M-N)}{M-2}$ for $N > \lceil 3M/4 \rceil$ and $P_a = 1$ for $\lceil M/2 \rceil \leq N \leq \lceil 2M/3 \rceil$. Hence, we have $P_a = \min\{\frac{3(M-N)}{M-2}, 1\}$.

It thus completes the proof.
the statistical perspective, let $p$ and has unique stationary and limiting distribution. From the switching probabilities from $m$, the queueing network is irreducible and aperiodic. Considered as a Markovian process. 

When the system can be seen as a discrete time queueing network with waiting room of infinite length and sensors as customers, the features that the customer will switch server driven by states of neighboring servers.

For simplicity, each accessing sensor is set to wait and access the accessed sensor from the switching probabilities from $m$. According to Theorem 2.3 in [28], each queueing process on each channel can be obtained as

$$P_m = \begin{pmatrix} 1 - \lambda_0^m \mu_0^m & 1 - \lambda_1^m \mu_1^m & \vdots & 0 \\ \lambda_0^m \mu_0^m & 1 - \lambda_1^m \mu_1^m & \vdots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & \cdots & 1 - \lambda_m^m \mu_m^m \end{pmatrix}.$$  \tag{15}

Denote $\Pi_m = [\pi_0^m, \pi_1^m, \ldots, \pi_m^m, \ldots]$ as the probability distribution of different queue lengths of $C_m$ at the steady state. We have the balance equation [28] as follows:

$$\Pi_m = P_m \Pi_m.$$  \tag{16}

Normalizing (16) by $\sum_{k=0}^{\infty} \pi_k^m = 1$, we obtain

$$\pi_0^m = \left(1 + \sum_{k=1}^{\infty} \frac{\prod_{j=0}^{k-1} \lambda_j^m (1 - \mu_{j+1})}{\prod_{j=1}^{k} (1 - \lambda_j^m) \mu_j^m}\right)^{-1},$$  \tag{17}

$$\pi_k^m = \frac{\prod_{j=0}^{k-1} \lambda_j^m (1 - \mu_{j+1})}{\prod_{j=1}^{k} (1 - \lambda_j^m) \mu_j^m} \pi_0^m, \quad k \geq 1,$$  \tag{18}

where $m = 1, 2, \ldots, M$. Since the LEQ-AutoCS rules only concern whether the neighboring channels are idle or not, we use $\pi_n^m$ to denote the probability that the channel is occupied. Substituting (13) and (14) into (17) and (18), we have

$$\pi_0^m = \left(1 + \frac{\alpha_m}{1 - \alpha_m}\right)^{-1},$$  \tag{19}

$$\pi_+^m = 1 - \pi_0^m,$$  \tag{20}

where

$$\alpha_m = \frac{p_m (1 - \mu - p_m, m-1 - p_m, m+1)}{(1 - p_m) (\mu + p_m, m-1 + p_m, m+1)},$$  \tag{21}

$$\gamma_m = \frac{p_m + p_m, m-1 + p_m, m+1}{p_m},$$  \tag{22}
for all \( m = 1, 2, \ldots, M \).

Then, according to the conditions defined in the LEQ-AutoCS rules, the switching probabilities at the steady state can be calculated as follows:

\[
p_{m,m+1} = (1-p_{m+1})\pi^+_m \pi^+_m \pi^0_{m+1}, \quad (23)
\]

\[
p_{m,m-1} = (1-p_{m-1})\pi^0_m \pi^+_m \pi^+_m. \quad (24)
\]

Theoretically, we can substitute (19) and (20) to solve the equations of (23) and (24) to acquire \( p_{m,m+1} \) and \( p_{m,m-1} \) for all \( m \in \{2, \ldots, M-1\} \). However, the order of equation will increase by each iteration, making the explicit solution intractable. Alternatively, we can use MATLAB to get the numerical solutions. The numerical examples are presented in the following section. Then, the performance metrics of spectrum sharing defined in (2)-(4) in Subsection III-B can be reformulated by the queueing network model, as shown in the following proposition.

Proposition 1: The \( U_m, U \) and \( U_f \) in the queueing network model can be reformulated as

\[
U_m = \pi^+_m, \quad (25)
\]

\[
U = \frac{1}{M} \sum_{m=1}^{M} \pi^+_m, \quad (26)
\]

\[
U_f = \frac{(\sum_{m=1}^{M} \pi^+_m)^2}{M \sum_{m=1}^{M} \pi^+_m}. \quad (27)
\]

Proof: The proof is omitted since it is easy to obtain the statistical utilization of each channel \( \pi^+_m \), and the system utilization is the mean of \( \{ \pi^+_m \}, m = 1, 2, \ldots, M \).

VI. EXPERIMENT RESULTS

A. Experiment setup

In this work, we focus on the spectrum sharing within the FieldNet as shown in Fig. 2. Hence, we build a prototype system of FieldNet based on USRPs and PXI platform to validate the effectiveness of the proposed LEQ-AutoCS rules. As shown in Fig. 7(a), the FieldNet consists of eight NI USRP 2921 devices (taken as sensors equipped with software-defined wireless transceiver) and a PXI extensions platform (taken as the AP). Fig. 7(b) shows the configuration of USRP. With WXB daughter board acting as duplex RF transceiver front-end, USRP receives RF signal and converts it to the baseband signal, then passes it to signal process module in LabVIEW. This module charges for spectrum sensing and decision making. Conversely, the signal process module generates the baseband signal to USRP together with RF transceiver configuration parameters including operating radio frequency, bandwidth of RF transceiver, and RF gain control. We set up 8 radio channels in the experiments, from 2.4GHz to 2.44GHz, with 5MHz bandwidth of each channel. Each USRP has 5MHz transmitting bandwidth and 15MHz receiving bandwidth, respectively. The PXI platform with 5663E vector signal analyzer works as the AP with 8 air interfaces, and it covers 40MHz bandwidth in the experiments. The transmission power of each USRP is 0dBm. Time slot is set to 50ms and sub-slot for channel switching is set to 5ms. The period of each experiment is 100,000 time slots. An accessing sensor will give up the accessing after 10 tries. The departure probability is identical since that channels are homogeneous, and set \( \mu = 0.125 \). We assume that the arrival probabilities of the channels, i.e., \( \{p_m\}, m = 1, 2, \ldots, 8 \), follow the Gauss distribution:

\[
p_m = \frac{1}{\sqrt{2\pi}\sigma} \exp \left( -\frac{(m - \mu)^2}{2\sigma^2} \right),
\]

where variance \( \sigma \) is set to 0.5. Normalizing the maximal \( p_m \) to 0.8\( \mu \), we obtain a set of values of \( \{p_m\} = \{0.0001, 0.0001, 0.0018, 0.1, 0.1, 0.0018, 0.0001, 0.0001\} \)\(^1\) for the first case, where the sensors mainly arrive at channels \( C_4 \) and \( C_5 \). Normalizing the maximal \( p_m \) to 1.5\( \mu \), we set another set of \( \{p_m\} = \{0.0001, 0.0001, 0.0034, 0.1875, 0.1875, 0.0034, 0.0001, 0.0001\} \) for the second case, where both \( p_4 \) and \( p_5 \) are larger than \( \mu \), implying that \( C_4 \) and \( C_5 \) are overloaded.

B. LEQ-AutoCS rules vs. dynamic accessing based strategies

We compare the proposed scheme with two existing dynamic channel accessing methods: round-robin method (RR) [19, 29], and pseudo random sequence based method (PR) [30]. With the round-robin method, accessing sensors perform spectrum sensing in a round-robin way from low frequency to high frequency.

\(^1\)In the analysis of queueing networks, the arrival probability \( p \) is set to \( 0 < p < 1 \). In order to make sense of the accessing sensor arrival model in queueing networks, here the \( p_1, p_2, p_7, p_8 \) are chosen as a small positive number such as 0.0001.
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channel to high frequency channel to search for available channels. With the pseudo random sequence based method, accessing sensors carry out spectrum sensing according to the predefined pseudo random sequence to search for available channels. Let ‘LS’ be short for LEQ-AutoCS rules and ‘NS’ represent the strategy without spectrum sharing. We investigate six scenarios with different spectrum sharing strategies: ‘NS’, ‘RR’, ‘PR’, ‘LS’, ‘RR+LS’ and ‘PR+LS’, where the latter two strategies adopt the LEQ-AutoCS rules together with ‘RR’ and ‘PR’ access control methods, respectively.

In the experiments, the statistical numbers of channel switchings between the neighboring channels are provided in Table I, where $S_{ij}$ denotes the channel switching from $C_i$ to $C_j$. The statistical analysis of channel switching probabilities is shown in Fig. 8. It can be seen that with LEQ-AutoCS rules, accessed sensors are capable of switching from high crowded channels to relatively sparse ones. Specifically, on the lower channels $C_1 \sim C_4$, the channel switching probabilities from higher channels to lower ones are larger, and on the higher channels $C_5 \sim C_8$, the channel switching probabilities from lower channels to higher ones are larger.

The theoretical channel switching probabilities are also presented in Table II. From the comparison result shown in Fig. 8, it can be seen that the channel switching probabilities from the experiments are basically consistent to the theoretical results.

Then we evaluate metrics: channel utilization $U_m$, system utilization $U$ and Jain’s fairness $U_f$. The comparison results of channel utilization are shown in Fig. 9. From Fig. 9(a), it can be seen that in the scenarios ‘NS’, ‘RR’ and ‘PR’, we have similar channel utilization, and ‘LS’, ‘RR+LS’ and ‘PR+LS’ are similar in case I. However, in the scenarios with LEQ-AutoCS rules, the loads on different channels are effectively balanced and thus the channel utilization is more even. From Fig. 9(b), in case II when the arrival rate is increased, $C_4$ and $C_5$ are overloaded; but not surprisingly the LEQ-AutoCS rules effectively alleviate the overloaded phenomenon by balancing channel utilization among $M$ channels. The theoretical results according to calculation in equation (25) are also showed by the dash lines noted by ‘Theo’. Note that in the theoretical analysis, only the channel switching of accessed sensors with LEQ-autoCS rules is considered; each accessing sensor is set to wait and access on its initial channel fixedly. Hence, the results show that the ‘Theo’ lines for both cases are not as even as the lines of ‘LS’, ‘RR+LS’ and ‘PR+LS’. However, ‘Theo’ lines indicate that even in such scenario, the LEQ-autoCS rules achieve more even channel utilization than the scenarios without them.

Fig. 10 shows the statistics of utilization and fairness of spectrum usage. For case I, the system utilization is similar for different scenarios because there are few lost packets. However, as sensors mainly arrive at channels $C_4$ and $C_5$, the strategies ‘NS’, ‘RR’ and ‘PR’ cannot rapidly response to the traffic loads, which results in low fairness. On the other hand, the strategies with ‘LS’ achieve high fairness of channel usage by autonomous channel switching. As the arrival rates increase in case II, the system utilization of ‘NS’ is obviously
lower than other strategies. With other spectrum sharing strategies, the congestion is alleviated. Different scenarios lead to different fairness of spectrum usage. The best performance can be achieved when ‘LS’ works together with ‘RR’ or ‘PR’.

Fig. 11 shows the distribution of the waiting time on the channels. Both cases confront with unbalanced distribution of the waiting time due to the different loads on different channels. Especially for case II, the waiting time for channels

$C_4$ and $C_5$ are even extremely large as the both channels are overloaded. However, with the spectrum sharing strategies, the traffic loads can be balanced. Then, the waiting time is effectively reduced and its distribution becomes more even. It also can be seen that the LEQ-AutoCS rules perform better than ‘RR’ and ‘PR’, and the best efforts can be obtained by ‘LS+RR’ and ‘LS+PR’. Intuitively, congestion on specific channels would result in low channel access probability. In the following, we evaluate the failed accesses and the mean waiting time of sensors. The results are listed in the Table III and Table IV. There are lots of failed accesses in the ‘NS’ since the congestion occurs. With LEQ-AutoCS rules, the congestion is relieved and the failed accesses are greatly reduced for both cases (for case I, the failed access is perfectly avoided). This implies that LEQ-AutoCS rules provide a higher spectrum access probability for sensors. Although ‘RR’ and ‘PR’ can also effectively reduce the failed accesses, the LEQ-AutoCS rules bring lower mean waiting delay for sensors as shown in Table IV. With the LEQ-AutoCS rules, the mean waiting delay of sensors is lower than 1/2 of the delay based on ‘RR’ and ‘PR’, since the LEQ-AutoCS rules promote the evener channels’ usage and provide lager channel access
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D. Discussion for the scenarios with interference

If there exists a wide-band interference, it would block the data transmissions and greatly decrease the performance of communications with different spectrum sharing methods. In this subsection, we investigate how LEQ-AutoCS rules work in the scenarios with narrow-band interference. For example, the interference signal exists on channel $C_m$, then transmissions set up on $C_m$ will be blocked. Since the sensing range of each sensor covers 3 channels, the sensor on $C_{m-1}$ will observe that $C_m$ is occupied, and so will sensor on $C_{m+1}$ do. They will not switch to $C_m$ according to the rules. As a result, the channels are divided into two segments, $C_1 \sim C_{m-1}$ and $C_{m+1} \sim C_M$. The sensors in each segment would approach to a new equilibrium of channels’ usage under the LEQ-AutoCS rules. With spectrum sensing ability, each sensor will autonomously avoid the interfered channel. But when the interference disappears, the channel will be reused. Then, the LEQ-AutoCS rules would promote the even usage of the whole spectrum and approach to the equilibrium. In other words, the LEQ-AutoCS rules can adapt to the scenarios with narrow-band interference, where the interference is just considered as a stubborn user which does not switch channel.

VII. CONCLUSIONS

An even-spectrum-usage targeted spectrum sharing scheme has been proposed for industrial wireless sensor networks so that the spectrum utilization and fairness of spectrum sharing is studied. The TDMA reservation based strategy for spectrum access probability.

In summary, the LEQ-AutoCS rules can be applied to improve the spectrum utilization, fairness of spectrum usage and the spectrum access probability. Moreover, the proposed rules are compatible with other accessing control based schemes to further improve the performance.

C. LEQ-AutoCS rules vs. TDMA reservation based strategy

In this subsection, the comparison between LEQ-AutoCS rules and TDMA reservation based strategy for spectrum sharing is studied. The TDMA reservation based strategy employs contention free scheduling method as used in WirelessHART [8]. Specifically, each channel is allocated to the fixed sensors by designing a multi-channel superframe. The superframe consists of several periods named guaranteed time slots (GTS). The GTSs on one channel are scheduled to the sensors, considering their workloads. For simplicity, we set the arrival rate at each channel to be equal and the arrival of transmission tasks of each sensor is a independent Bernoulli random process. In this experiment, we have two sensors on each channel. The total rates of all sensors are 0.20 for Case I and 0.38 for Case II, respectively. The packet number of each transmission, i.e., $1/\mu$, is fixed to 8. Under these settings, we observe the spectrum access delay of the two spectrum sharing strategies.

The statistical results are presented in Table V. The spectrum sharing by LEQ-AutoCS rules achieves a much lower mean access delay than that by TDMA reservation based strategy. Particularly, with LEQ-AutoCS rules, the average delay of all sensors (noted by ‘Ave.’ in Table V) is lower than 1/50 of that by TDMA reservation based strategy. This is because the TMDA reservation based spectrum access is normally suitable to the periodic data delivery. As for the case of random data delivery, it is inadequate to quickly response to the random arrival of transmission task by the TDMA strategy, as the GTSs are scheduled periodically and statically. Hence, the LEQ-AutoCS rules outperform the TDMA reservation based strategy on the performance of spectrum access delay.

![Fig. 11. Waiting time of six scenarios for both cases.](image-url)

<table>
<thead>
<tr>
<th>Case</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
<th>$C_4$</th>
<th>$C_5$</th>
<th>$C_6$</th>
<th>$C_7$</th>
<th>$C_8$</th>
<th>Ave.</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS</td>
<td>0.05</td>
<td>0.04</td>
<td>0.03</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
<td>0.02</td>
<td>0.06</td>
<td>0.03</td>
</tr>
<tr>
<td>TDMA</td>
<td>3.85</td>
<td>3.62</td>
<td>3.73</td>
<td>4.14</td>
<td>3.90</td>
<td>3.76</td>
<td>3.90</td>
<td>3.69</td>
<td>3.82</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
<th>$C_4$</th>
<th>$C_5$</th>
<th>$C_6$</th>
<th>$C_7$</th>
<th>$C_8$</th>
<th>Ave.</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS</td>
<td>0.23</td>
<td>0.11</td>
<td>0.08</td>
<td>0.06</td>
<td>0.07</td>
<td>0.07</td>
<td>0.09</td>
<td>0.33</td>
<td>0.14</td>
</tr>
<tr>
<td>TDMA</td>
<td>0.65</td>
<td>0.27</td>
<td>0.79</td>
<td>0.88</td>
<td>0.69</td>
<td>0.45</td>
<td>0.34</td>
<td>0.51</td>
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</tr>
</tbody>
</table>
usage, and probability of spectrum access for new transmission requests can be improved compared to standardized industrial wireless protocols. The so-called LEQ-AutoCS rules have been devised for accessed sensors to autonomously switch channels by imitating the behavior of biological agents to achieve collective motion with only local observation and action. It has been demonstrated that the equilibrium of spectrum usage can be achieved under the LEQ-AutoCS rules. Moreover, the lower bound of spectrum access probability at the equilibrium and the upper bound of the convergence time to equilibrium have been derived as well. The proposed method provides an effective scaling way for large-scale industrial wireless applications with limited spectrum resource. The experiment results demonstrate the effectiveness of the proposed spectrum sharing scheme. In our future work, we will investigate the issue of autonomous channel switching design with the consideration of sensors’ imperfect sensing.

REFERENCES
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