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# Mitigation of Mutual Interference In IEEE 802.15.4-based Wireless Body Sensor Networks Deployed In E-health Monitoring Systems

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**Abstract** One of the main issues experienced in Wireless Body Sensor Networks (WBSNs) is the destructive impacts of "mutual interference" caused by neighboring WBSNs on each other's performance. Research communities have proposed several approaches to mitigate the impacts of mutual interference on the reliability of data transmission and sensor's energy consumption. However, the proposed approaches came with a number of limitations, such as significant modification of the standard protocol or imposing a high level of complexity. In this paper, a range of schemes are proposed, and their performances are evaluated in the presence of mutual interference experienced in a dynamic environment. More specifically, we consider a situation where a large number of people (each individual covered with a number of sensors to fetch the human vital sign) are gathered at a sport centre to enjoy an event. In such a dynamic environment, people would highly likely experience mutual interference which would destructively impact on WBSN's performances and eventually would result in an unreliable medical outcome. A simulation study is conducted in which a set of schemes proposed that indicates a gradual improvement of WBSN's performances in terms of reliability of data transmission and sensor's energy consumption. Our obtained results show that the frequency-adaptation strategy combined with phase-adaptation approach significantly improves the performance of WBSNs in the presence of mutual interference in a dynamic environment. Moreover, an experimental study is carried out to examine the

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feasibility of implementing the predominant scheme on real-world sensor devices and to further support the outcome of the simulation study.

**Keywords** Wireless Body Sensor Network · IEEE 802.15.4 · Performance Evaluation · Mutual Interference, Frequency Utilisation

## 1 Introduction

Wireless Body Sensor Networks (WBSNs) are regarded to play an important role in medical and heath-related applications [28] and [5]. Since such medical applications are dealing with processing human vital signs, maintaining high reliability of data transmission and low energy consumption seem to be crucial. IEEE 802.15.4 standard protocol [2] is arguably one of the suitable standardised technologies for WBSNs as it is a well-established technology for Personal Area Networks (PAN) whose main characteristics are low-cost, low-power and available mature sensor devices. Although WBSNs seem to be strongly beneficial in both medical and non-medical applications, some of their characteristics create quite a number of issues, including mutual interference, inefficient frequency spectrum utilisation, and energy constraints. One of the most challenging issues is the mutual interference caused by neighbouring WBSNs. As the number of co-located IEEE 802.15.4-based WBSNs becomes larger in an operating frequency, their performance will be eventually influenced by the mutual interference. In fact, mutual interference eventually causes significant performance degradation due to inefficient channel utilisation. This paper evaluates the performance of WBSNs while experiencing mutual interference, which is regarded as the interference caused by two neighbouring WBSNs on one another. The mutual interference is basically different than the "external interference". The former is the interference caused by the same technologies on each other (WBSNs) while the latter is the interference that comes from other technologies, e.g. WiFi or Bluetooth on WBSNs. The external interference does not usually provide useful information. However, the mutual interference contains useful information such as the number of occupants of a channel (operating frequency) and their active periods which are quite helpful to have a good estimation about frequency spectrum utilisation. This paper discusses a situation where a large number of people come together at a place, e.g. sport centre or cinema, and their attached WBSNs have to compete to gain access to the frequency spectrum. As a result, it is highly likely to experience a large number of packet collisions and eventually, a high packet loss rate. High packet loss rate results in experiencing low reliability of data transmission, which in turn degrades the reliability of collected human vital signs. This is mainly caused by unsynchronised nature of WBSNs, which makes them compete with each other to gain access to the frequency spectrum. There is a possibility that two neighbouring WBSNs choose the same operating frequency and the same time slot as their active periods which eventually results in experiencing packet collisions.

This article presents an evolutionary process of schemes proposed to mitigate frequency interference amongst WBSNs when located at a close proximity and dynamically utilise operating frequencies in a random fashion. More specifically, this paper presents a range of schemes that step-by-step enhance the WBSN's performance in terms of data transmission reliability and energy consumption in the presence of mutual interference in a dynamic environment. Moreover, these schemes are designed in such a way that they incur minimum changes to the IEEE 802.15.4 standardised Medium Access Control (MAC) protocol stack and can be easily implemented on the real-world sensor devices. A simulation study has been carried out to determine the impacts of mutual interference on the WBSN's performance (i.e. successful transmission of data packets and sensor energy consumption) in a dynamic environment. The conducted simulation study has also revealed that the combination of both frequency-adaptation and phase-adaptation approaches – the predominant scheme – results in experiencing the highest reliability of data packet transmissions as well as the lowest sensor's energy consumption among the proposed scheme. An experimental study is also carried out to determine the feasibility of implementing the functionality of predominant scheme on real-world sensor devices which is another major contribution of this article. The remainder of this paper is as follows: Section 2 explains the functionality of the IEEE 802.15.4 MAC protocol standard along with a brief introduction of a few system parameters. Section 3 presents a brief history of interference mitigation schemes and related works. The system model, the energy consumption model and the dynamic environment arrangement are discussed in their relevant subsections in Section 4. Moreover, this section explains the system model used for the experimental study. The results of both simulation and experimental studies are presented and discussed in Section 5, followed by the conclusions and the future work in Section 6.

## 2 IEEE 802.15.4 Background and Functionality

The IEEE 802.15.4 standard is a well-designed protocol for wireless sensor networks whose main characteristics are low-powered and low-cost components. Therefore, this standardised protocol has also been considered as an underlying technology for WBSNs as well, and it will arguably remain a serious contender in the field of WBSN for quite some time. The architecture of this standard comprises the Physical (PHY) layer and the MAC layer. The physical layer contains the Radio Frequency (RF) transceiver and the low-level control mechanism, while the MAC layer provides access to the physical operating frequency (channel) for any transmission purposes.

In this paper, we are going to focus on 2.4 GHz frequency spectrum offered in PHY layer simply due to the availability and the accessibility of the popular ChipCon CC2420 transceivers that are compliant to this band. The data rate in this band is 250 kb/s. The 2.4 GHz band is further subdivided into 16 non-overlapping operating frequencies. Each operating frequency is two MHz wide, and there is a 5 MHz distance between the centres of two adjacent operating frequencies. To evaluate the impact of mutual interference on WBSN's performance, we only consider the interference caused by neighbouring WBSNs, and the adjacent channels interference is disregarded [27]. To provide the possibility of sharing the 2.4 GHz frequency spectrum with other technologies, e.g. WiFi and Bluetooth, The PHY layer in IEEE 802.15.4 uses the Offset Quadrature Phase-shift Keying (O-QPSK) modulation along with interference mitigation mechanisms such as Direct Sequence Spread Spectrum (DSSS) and the Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA).

There are two modes of operation in IEEE 802.15.4 MAC layer, namely: beacon-enabled and non-beacon-enabled modes. In the beacon-enabled mode, time is divided into time frames called Superframes. Superframes are further divided into an active and an inactive periods. According to the IEEE 802.15.4 standard, all devices transmit and receive necessary information during the active period and turn to sleep mode (with the least energy consumption) during the inactive period. A superframe starts with the transmission of a beacon packet by a central sensor device called "PAN coordinator" or simply "coordinator". The beacon packet carries some information, e.g. network configuration and the pending downlink data packets, which are consumed by the sensor devices associated with the coordinator. The coordinator does not perform a carrier-sense operation for transmitting the beacon packets. The length of the superframe and the relative length of the active period within a superframe are determined in such a way that the requirements of the application layer are fulfilled. The duration of time between two consecutive beacon packets is called Beacon Interval (BI) and ranges from 15 ms to 245 s. The duration of the active period is called superframe Duration (SD). The lengths of both BI and SD are calculated by using Beacon Order (BO) and Superframe Order (SO), respectively [3]. Some guaranteed time slots (GTSs) can be considered to allocate to sensor devices at the end of the Contention Access Period (CAP). The GTSs are free of running the CSMA-CA scheme. However, authors in [29] have shown that the carrier-sensing approach can play a key role to achieve higher performance gain in the presence of interference. The length of *duty cycle* , i.e.active period and beacon intervals, is configurable. A duty cycle of a WBSN is denoted as a superframe that consists active period – which is a duration of time when sensors of a WBSN use CSMA to compete with each other and gain access to the medium – and inactive period – which is the duration of time when sensors sleep to save energy. The active period is also referred to as the WBSN time slot and always starts after the transmission of a beacon packet. The exact time that the beacon packet is transmitted by the coordinator determines the start of the activity phase and thus active period followed by the transmission of the beacon packet is regarded as the WBSN time slot. Please refer to [2] to find out how duty cycle parameters are determined.

Specifically, the beacon period is given by

$$BI = aBaseSuperframeDuration \cdot 2^{BO} \tag{1}$$

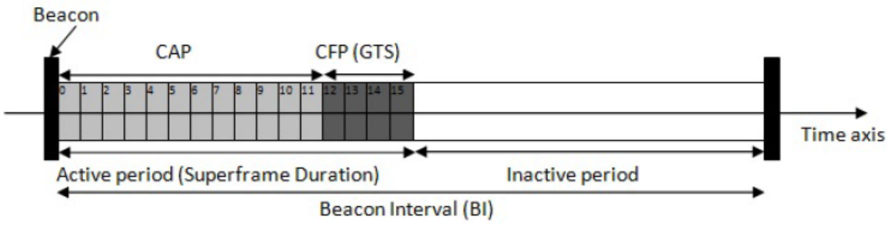

**Fig. 1** Superframe structure of IEEE 802.15.4

where $aBaseSuperframeDuration = 15.36$ ms for the 2.4 GHz PHY, and $BO \in \{0, \ldots, 14\}$ is the beacon order. The duration of the active period is given by

$$SD = aBaseSuperframeDuration \cdot 2^{SO} \tag{2}$$

with $0 \leq SO \leq BO \leq 14$ and where $SO$ is the superframe order. The values of BO and SO are set to fulfil a number of requirements, e.g. the number of packet re-transmissions, packet time-to-live and transmission ratio of data packets. The associated sensor devices are informed about the currently-employed BO and SO values via receiving the beacon packet, which is transmitted by their coordinator at the beginning of each superframe. Figure 1 depicts the superframe structure of IEEE 802.15.4 standard MAC protocol.

In this paper, it is assumed that all sensor devices use CAP duration to transmit their collected data to the coordinator. This is the more robust option in the presence of interfering WBSNs, as the CAP allows nodes to use a CSMA-CA access scheme, which at least provides some basic protection against competing packets. The coordinator has to stay awake for the entire active period, whereas the sensor devices only have to wake up to receive the beacons and can otherwise sleep when they have nothing to transmit. In this paper, changing the phase means to change the exact time that the coordinator transmits the beacon packet, which is a real value selected from (0, 1). In the beacon-enabled mode, since the beacon packet is always followed by the active period (WBSN time slot), these two terms are used interchangeably. Figure 2 is a sequence diagram that illustrates the communication process between a coordinator and its associated sensor.

When a sensor does not receive four consecutive beacon packets, it becomes orphan. An orphan sensor assumes that the synchronisation with its coordinator has been lost. Therefore, an orphan sensor searches through a list of available channels in order to find its PAN coordinator again (i.e. to receive the next beacon from it). It must be noted that a sensor device, whilst being orphan, is not able to send any data packets, so data packets that overflow from its buffer are counted as lost.

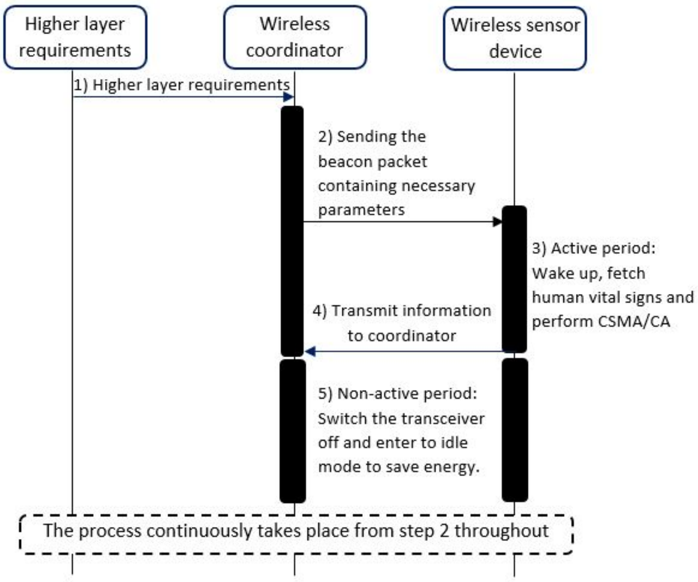

**Fig. 2** Sequence diagram illustrating flow process between a coordinator and its associated sensor

## 3 Related Work

Over the past decade, both mutual and external interference have been studied and their impacts on the WBSN's performance have been determined. Our previous investigation on mutual interference [18] and [20] have clearly explained the inefficient channel utilisation of IEEE 802.15.4 standard protocol. "Frequency-adaptation" approach [21] and [17] in a static environment has improved the reliability of data packet transmission in the presence of both external and mutual types of interference. In the follow-up research [19] "Adaptive Phase-shifting" scheme has been proposed, and its performance was evaluated against IEEE 802.15.4 standard in an ever-changing environment. However, its higher level of complexity is considered as a major limitation, even though deployment of this scheme resulted in significant improvement compared to the frequency-adaptation schemes in isolation. In another attempt, authors in [16] surveyed the effective system parameters in IEEE 802.15.4 MAC protocol standard and determined their impacts on WBSN's performance in the presence of mutual interference. The impacts of using the same frequency band on the performance of IEEE 802.15.4 have been determined in [6]. This study proposed a "Dynamic Coexistence Management" mechanism to reduce the destructive impacts of sharing the same operating frequencies by using the gaps in an operating frequency. Authors in [14] and [22] have conducted an experimental study to evaluate the impact of interference on WBSN's successful transmission of data packets. They proposed a scheme to utilise the gaps in an operating frequency. Other approaches such as Multi-channel Superframe Scheduling (MSS) [27] and [11] propose to use multiple channels with to avoid beacon collisions and compared their proposed scheme (MMS) with time-division superframe scheduling approach. An algorithm is proposed in [12] in which the channel utilisation can be improved, and beacon collisions can be avoided by adjusting the superframe. "Superframe Scheduler" is another approach in which a virtual channel is created through scheduling a superframe and choosing a logical channel [10]. The IEEE 802.15.4 beacon-enabled MAC protocol has been comprehensively surveyed in [8]. Some of the referenced papers have shown higher performance gains but at higher costs and complexity. In some others, the significant modification of the IEEE MAC protocol to avoid internal interference has made them less interesting. The IEEE 802.15.6 standard [3] has introduced four strategies to better deal with mutual interference between BANs, namely: beacon-shifting, channel-hopping, active superframe interleaving and B2-aided time-shifting (only applicable in the non-beacon enabled mode). In [9] the performance of the beacon shifting approach (proposed in the IEEE 802.15.6 MAC protocol) is assessed and compared to a "flexible beacon scheduling" scheme where a coordinator performs the carrier sensing before beacon transmission. The obtained results show significant improvement over the beacon-shifting approach. Authors in [24] employed Monte Carlo simulation method to analyse the influence of co-channel interference on the error probability of IEEE 802.15.4 to derive an accurate analytical model. "Autonomous collision-free Enhanced Beacon scheduling policy" is introduced in [7] to avoid beacon collisions as a result of interference in IEEE 802.15.4. The above-mentioned related works are mainly concerned with a static environment where WBSNs remain active for the entire simulation or experimentation time. This paper, however, particularly focuses on the dynamic environment where WBSNs are dynamically exposed to various magnitude of interference which is closer to the real-world experience. To the best of author's knowledge, the performance of WBSNs – in the presence of mutual interference – has not been evaluated in dynamic environments as there is a possibility of experiencing a higher level of agitation and performance degradation compared to static environments.

## 4 System Model

This section explains the considered performance parameters and scenarios for both simulation and experimentation studies.

### 4.1 Simulation study

In our simulation study, an individual WBSN consists of four sensor devices and a coordinator. The sensor devices and the coordinator form a star topology where sensor devices are equidistantly spread out on a circle of one meter

**Table 1** Parameters used for simulation

| | | |
|---|---|---|
| **Application Layer (CC2420) Parameters** | | |
| Packet Inter-arrival Time | $0.01536s \times 2^{BO}$ | s |
| Coordinator start up delay | Exponentially distribution | s |
| Sensor start up delay | 8 | s |
| Data payload | Uniformly distributed between 64 and 102 | integer byte |
| **MAC Layer (CC2420) Parameters** | | |
| Max Frame re-tries | 9 | scalar |
| Max Lost Beacons | 4 | scalar |
| Beacon Order | 6 | scalar |
| Superframe Order | 4 | scalar |
| Buffer size | 32 | scalar |
| **Physical Layer (IEEE 802.15.4) Parameters** | | |
| TX power | -25 | dBm |
| Data rate | 250 | kbps |

radius around the coordinator device. $\delta$ number of WBSNs (where $\delta \in \Delta$, $\Delta = \{50, 100, 150, 200, 250\}$) are placed at the close proximity to each other to create mutual interference along with avoiding hidden terminal situations. Moreover, this arrangement allows us to disregard the shadowing effect of the human body, eliminate packet losses coming from path loss or fading effects and ignore the impact of different transmit powers. Additionally, this article does not consider the impact of the on-body channel, gender, posture and different environmental factors on the WBSN performance. Hence, packet losses can only be attributed to packet collisions caused by mutual interference. All WBSNs are configured to the beacon-enabled mode.

Successful transmission of a data packet is defined as a data packet that is received at the receiver sensor device, and the corresponding acknowledgement is also received at the sender sensor device. If a sensor device does not receive the corresponding acknowledgement, it re-transmits the packet up to a specific number of retries. Sensor devices are configured to maintain their association, synchronisation and communication with their respected coordinator only. This means that the sensors have to wake up and receive all beacon packets sent by their coordinator, and if the sensor has not received four consecutive beacon packets, it becomes ”orphan” and scans the frequency channels according to the considered scheme (explained later) to re-associate to its corresponding coordinator. Moreover, the GTS is not configured in this simulation experiment as it is shown in [29] that the lack of carrier-sensing strategy in TDMA time slots in the presence of interference results in significant WBSN performance degradation. To provide a fair operational condition for all considered schemes, each PAN coordinator is switched on at a random time using an exponential distribution with a mean value of one second.

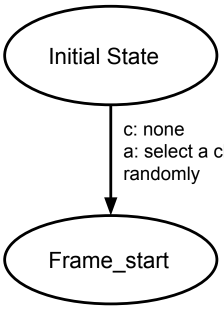

**Fig. 3** State machine diagram for the static-random scheme

### *4.1.1 Proposed Schemes*

In this subsection, a number of proposed schemes is explained:

*static-random scheme:* In this scheme, WBSNs are autonomously and randomly distributed (according to uniform distribution) across the entire frequency spectrum. The coordinator of a WBSN in this scheme do not perform any measurement. Each WBSN remains on its assigned operating frequency throughout. Therefore, an orphan sensor device would only need to scan the original operating frequency to re-associate to its coordinator. More specifically, an orphan sensor device only listens to its original operating frequency to receive beacon packets containing its associated coordinator PAN-ID, and no other operating frequencies will be examined. WBSNs are configured to start randomly and independently using an exponential distribution with the mean value of one second. This scheme is considered the baseline in our study as it closely follows the IEEE 802.15.4 MAC protocol standard, which represents the lower band of the achievable gain. Figure 3 depicts the state machine diagram for this scheme.

*static-initial-choice scheme:* In this scheme, the coordinator of a WBSN scans the entire frequency band at the very beginning of its activation, in a random fashion (uniform distribution), targeting an operating frequency with the smallest number of occupants. More specifically, the coordinator of a WBSN scans each operating frequency for a BI period to detect as many beacon packets as possible. Once the channel scanning for the current operating frequency is finished, it proceeds to the next operating frequency and repeats the same course of the act until all operating frequencies are exhausted. In case of finding more than one operating frequency with the same number of occupants, one of them will be chosen randomly. Similar to the static-random scheme, once the target operating frequency is determined, the WBSN remains there throughout. The following state machine diagram (Figure 4) indicates the flow process occurs in this scheme.

*dynamic-random-hopping scheme:* In this scheme, the coordinator of a WBSN continuously measures the quality of the current operating frequency.

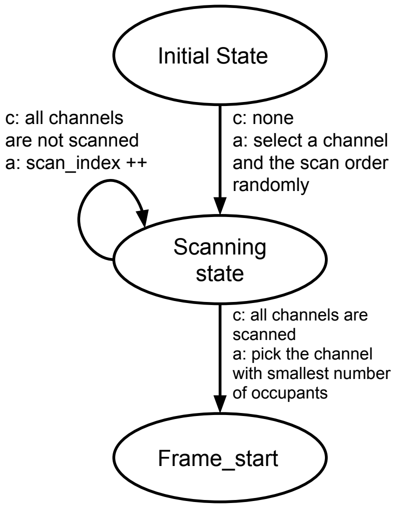

**Fig. 4** State machine diagram for the static-initial-choice scheme

The coordinator accomplishes that by counting the gaps between the sequence number of two consecutive received data packets and eventually, calculating the packet loss rate for that particular sensor device. If the average of calculated packet loss rate for all sensor devices exceeds the 5% threshold, the coordinator randomly (uniform distribution) chooses a new operating frequency (except the current operating frequency), informs its attached sensor devices and the whole WBSN hops to the new operating frequency. The coordinator includes the hopping information in the payload of four consecutive beacon packets. The associated sensor device, upon receiving at least one of these beacon packets, synchronises itself with the coordinator and its hopping time. Four consecutive beacon packets have been used – carrying hopping information – to increase the chance of receiving at least one of these beacon packets by the attached sensor devices. The calculation of packet loss rate occurs over a sliding window of 50 BIs. If the packet loss rate is lower than the 5% threshold, the window slides by one, and a new calculation will be made. This procedure continuously occurs throughout. If a sensor device becomes orphan, it scans the whole frequency spectrum to find its respected coordinator as the WBSN might have hopped to another operating frequency. The introduced packet loss calculation is suitable for relatively high data traffic rate. For other cases, when there are larger spaces between generated data packets, some other techniques such as moving-average estimator could be a better option to calculate the packet loss rate. Figure 5 shows the message flow process for dynamic-random-hopping scheme.

*dynamic-targeted-hopping scheme / continuous assessment:* In this scheme, the coordinator of a WBSN uses its inactive period to continuously scan other operating frequencies to maintain a general view of the number of WBSNs util-

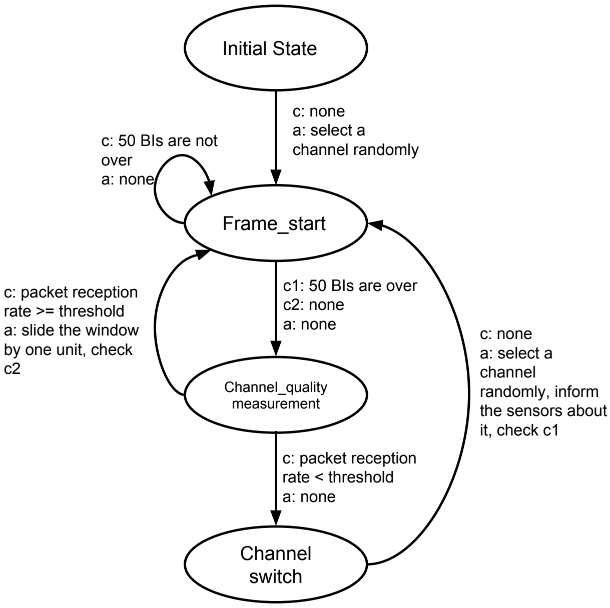

**Fig. 5** State machine diagram for the dynamic-random-hopping scheme

ising other operating frequencies. Scanning of the entire frequency spectrum occurs one operating frequency at an inactive period of a beacon interval (BI). More specifically, at the beginning of the inactive period, the coordinator of a WBSN jumps to a new operating frequency and counts as many other beacon packets as possible. When the inactive period is about to finish, the coordinator jumps back to its original operating frequency and resumes its activities with its associated sensor devices. This procedure takes places for another operating frequency in the upcoming inactive period and repeatedly occurs to cover all operating frequencies throughout. This measurement provides a better assessment when a WBSN is in need of changing its operating frequency as this measurement assists the coordinator to choose an operating frequency with the smallest number of occupants. Note that if multiple operating frequencies are found with the same smallest number of occupants, one of them will be selected randomly. The packet loss rate calculation procedure and informing sensor devices about the new operating frequency are similar to the line of activity described earlier for dynamic-random-hopping scheme. In this scheme, an orphan sensor device assumes that the coordinator has switched to another operating frequency, and therefore, the sensor device has to scan the entire frequency spectrum. Figure 6 depicts the state machine diagram for this scheme.

*Dynamic Phase Shifting scheme:* This scheme is completely distributed randomly, and the need to obtain a global consensus (, e.g. agreeing on the number of occupants in each operating frequency [19] and [15]) is eliminated.

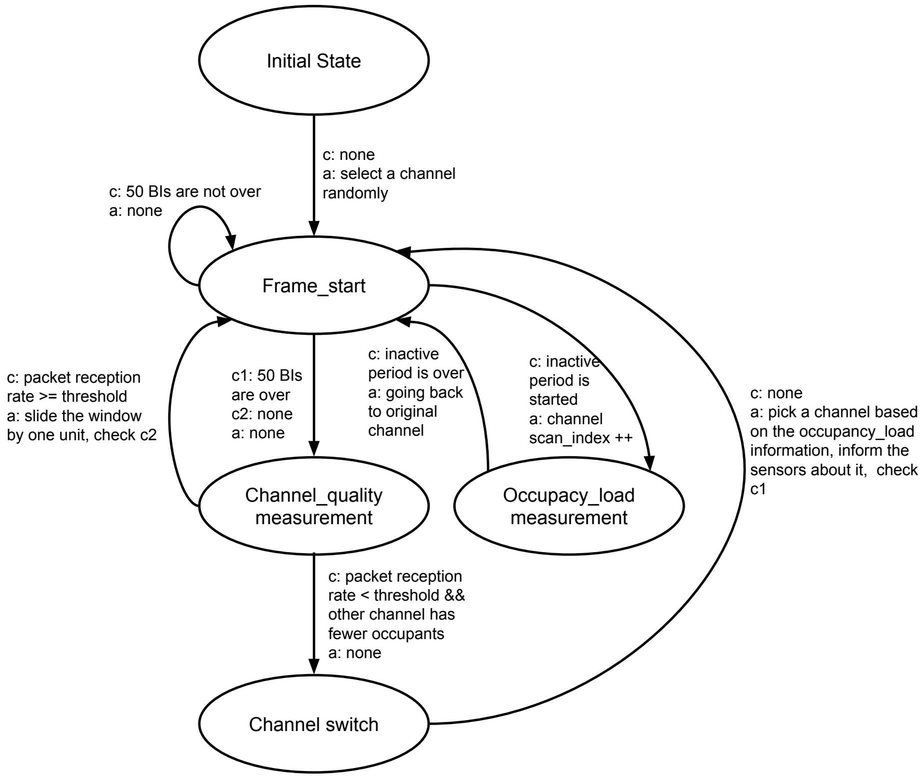

**Fig. 6** State machine diagram for the dynamic-targeted-hopping scheme

The DPS scheme mainly runs two procedures in parallel with insignificant interaction between them, namely: frequency adaptation and phase adaptation. Running these adaptation procedures requires the coordinator to include some information to the payload of its beacon packets. Since beacon packets can be observed by other coordinators, the information included in the beacon packets can also be viewed by other coordinators. This way, they can share their views and take actions accordingly. Due to the distributed nature of this scheme, randomised decisions are considered when actions are taken with a certain probability. This allows us to simply avoid oscillatory behaviour. The DPS scheme comprises of three main states: Initial-unsettled, Unsettled and Settled states. In order to understand these states, we first need to become familiar with two important terms that are used in the DPS scheme: *adaptation-period* and *jumping Probability*.

An adaptation-period is an integer multiplication of the number of beacon periods (or BIs). In this simulation study, two beacon periods are considered as an adaptation-period. During this period, a WBSN updates its observed packet loss rate, and any decision to jump to another phase will only be made at the end of the adaptation-period. At the end of the adaptation-period, if the packet loss rate has exceeded above a certain threshold, a WBSN jumps to a new phase. To jump to a new phase, the coordinator of a WBSN randomly (uniform distribution) selects a real number from (0, length of a beacon period) and informs its attached sensors in two consecutive beacon packets. The jumping probability, on the other hand, is a real value from $(0, 1)$. When the coordinator of a WBSN calculates the packet loss rate, it updates its jumping probability as well. If the jumping probability $T$ of a WBSN was above the threshold of $T_{threshold} = 0.5$, once the adaptation-period is over, the WBSN jumps to a new phase according to previously determined value from (0, length of a beacon period). The functionality of the jumping probability is explained more in details according to the behaviour of a WBSN in either of settled or unsettled state.

The behaviour of a WBSN in each of the three states is described as follows:

Initial-unsettled state: This state is the first point of activation for a WBSN in the DPS scheme. In this state, the coordinator collects the packet loss rate over 50 beacon periods. If the packet loss rate was above 2% (or below the satisfaction threshold of 98%), it transits to the unsettled state.

Unsettled state: In this state, A WBSN randomly (uniform distribution) selects a real number from (0, length of a beacon period), passes this information to its attached sensor nodes and the whole WBSN jumps to that phase. In this state, the jumping probability $T$ is set to the highest value $T := T_{high}$, which is 99%. This procedure repeatedly takes place until a suitable phase (time slot) is found in which the successful transmission of data packets is above the threshold of 98% (also known as a satisfied WBSN). A satisfied WBSN in the unsettled state transits to the settled state and sets its jumping probability to the lowest value $T := T_{low}$, which is 1%.

Settled state: In this state, the WBSN experiences less than 2% packet loss rate and considers itself satisfied. However, a satisfied WBSN in a settled state can become dissatisfied as other unsettled WBSNs may frequently change their phases and jump over the active period of the satisfied WBSNs. In this situation, the satisfied WBSN increases its jumping probability by $T := \min\{T + T_\alpha, T_{threshold}\}$ after the adaptation period, where $T_\alpha$ is a step with the value of 0.15 by which the jumping probability $T$ is increased, and $T_{threshold}$ bounds this growth. Note that the satisfaction threshold and $T_{threshold}$ are two different matters. The satisfaction threshold is 98% successful transmission of data packets, whereas $T_{threshold}$ is the threshold at reaching which, a WBSN transits to the unsettled state and follows activities instructed for a dissatisfied WBSN in that state. The main reason that a WBSN in the settled state may experience packet loss rate above the threshold and step-by-step increase the jumping probability would be sharing the same time frame (i.e. active period) with a number of unsettled WBSNs that frequently jump to another phase selected from (0, length of a beacon period). Every time that the packet loss rate is determined above the threshold (or the satisfaction rate degrades below the threshold of 98%) the jumping probability is increased by one step (increasing by a value of 0.15). This process happens until the

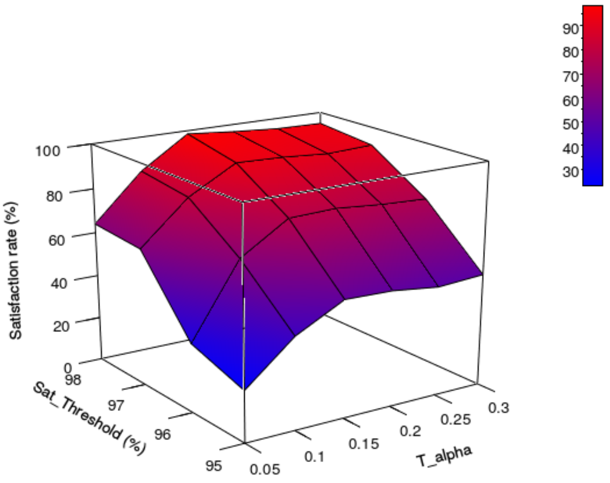

**Fig. 7** Satisfaction rate when $delta = 13$

jumping probability exceeds the threshold of 0.5. Which gives the WBSN in the settled state chances (three times) to stay in the same spot. By the fourth time if the packet loss rate is still above the threshold, the WBSNs in the settled state considers itself unsatisfied and informs its attached sensors to jump to another randomly selected phase and follows the activities set for the WBSN in an unsettled state. However, the jumping probability is reset to 1%, only when the satisfaction rate is above the 98% threshold. Therefore, there is no way that the satisfaction rate is below 98% and still after the fourth time evaluation the WBSN still stays on the same spot.

Employing this procedure allows the satisfied WBSNs to remain on their current phase (until the $T_{threshold}$ is reached) and push dissatisfied WBSNs to jump to other randomly chosen phases until they find proper phases (a phase in which the success rate is above the satisfaction threshold). Please note that the values of satisfaction threshold and $T_\alpha$ are determined after carrying series of simulation study on one channel with a different number of WBSNs. Figures 7 and 8 illustrate the trends of satisfaction rate when number of WBSNs for one channel $\delta \in \{13, 16\}$, satisfaction threshold $\in \{95\%, 96\%, ..., 98\%\}$ and $T_\alpha \in \{0.05, 0.1, 0.15, 0.2, 0.25, 0.3\}$.

Figures 7 and 8 suggest that the combination of $T_\alpha = 0.15$ and satisfaction threshold $= 98\%$ offers the highest satisfaction rate. Figure 9 shows the state machine diagram for the DPS scheme. Note that the threshold values considered for phase- jumping probability and frequency-hopping probability are configured to 0.5 or 50% to avoid scenarios in which a group of WBSNs choose the same operating frequency as their alternative future channel and

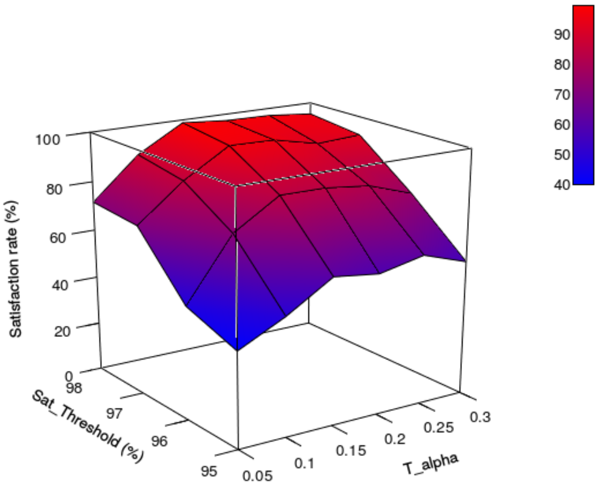

**Fig. 8** Satisfaction rate when $delta = 16$

hence avoiding challenges such as ping-pong problem. Further discussions can be found in [13].

One of the major contributions of the DPS scheme is the independent nature of finding a phase that results in experiencing satisfaction rate above the threshold. The WBSNs eventually find their suitable time slots to settle without the need of any global consensus or allocation of time slots. This is achieved with minimum modification of IEEE 802.15.4 standard. The frequency adaptation procedure is explained as follows: The coordinator of a WBSN initially generates a random order to scan the other channels. The coordinator scans a new channel for a duration of an inactive period to receive any other beacon packets and extracts the largest number of occupants being included among them. The coordinator, thereafter, returns to its original channel and scans it for a full beacon period to determine if any update is required (, e.g. changing in the number of occupants). Once a channel with the smallest number of occupants (with the difference of at least two WBSNs) is identified, the coordinator draws a random number from (0, 1) as a hopping probability. If the hopping probability was above the threshold of vale 0.5, the coordinator informs its attached sensors in two consecutive superframes (after adaptation period) and switch to the new channel, thereafter. Otherwise, it stays on the same channel and keeps scanning the frequencies. Such channel hopping strategy (using the hopping probability) is considered to decrease the chance of multiple WBSNs switch to the same operating frequency with the smallest number of occupants. This is mainly achieved by using the hopping probability and random channel scanning order. These two parameters effectively avoid a group of WBSNs to jump to the same operat-

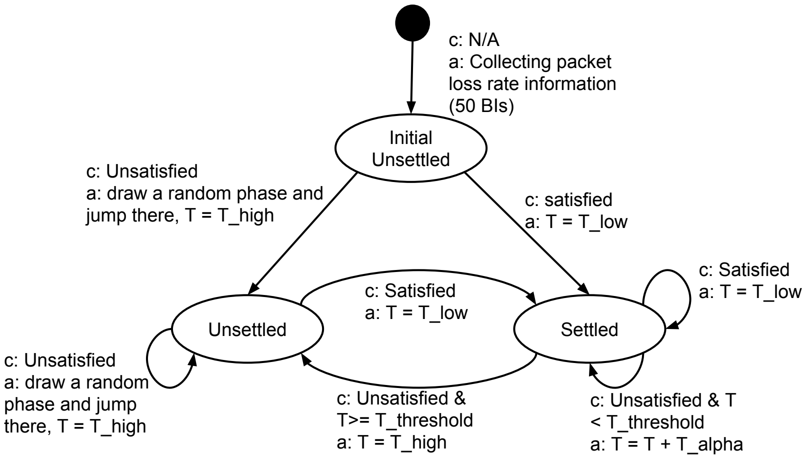

**Fig. 9** State machine diagram for phase-shifting procedure in the DPS scheme

ing frequency with the smallest number of occupants and hence avoiding the ping-pong problem. Moreover, this frequency hopping strategy is fairly similar to the frequency adaptation scheme mentioned earlier for dynamic-random-hopping and dynamic-targeted-hopping schemes which makes the comparison of these schemes more justifiable. The scanning procedure of other operating frequencies is a procedure that occurs repeatedly throughout, and switching to the channel with the smallest number of occupants occurs regardless of the current channel quality. The WBSN that has switched to the new operating frequency reset its current state to initial-unsettled state and start collecting the satisfaction information. The state machine diagram for frequency adaptation procedure in the DPS scheme is quite similar to the one shown for dynamic-targeted-hopping scheme. Figure 10 illustrates the state machine diagram for the frequency-adaptation procedure employed in the DPS scheme.

### *4.1.2 Energy Consumption Model*

Sensor devices are energy constraint. Therefore, the energy consumption of sensor devices is one of the major performance measures to evaluate the suitability of a scheme and particularly requires more attention when dealing with medial applications. In this simulation study, the energy consumption of a sensor device is mainly related to its transceiver (as elaborated in [4, 25]) and the power consumed by other components of WBSN nodes are ignored. The characteristics of the IEEE 802.15.4 compatible with ChipCon CC2420 transceiver [26] is used to model the energy consumption of the sensor transceiver. The transmit power and the voltage of the power supply component are fixed to -25 dBm and 3.3 v, respectively. In our energy model, there are three operational states in a single sensor device: sleep, transmit and receive states. The time spent in either of these operational states is collected individually. Thereafter,

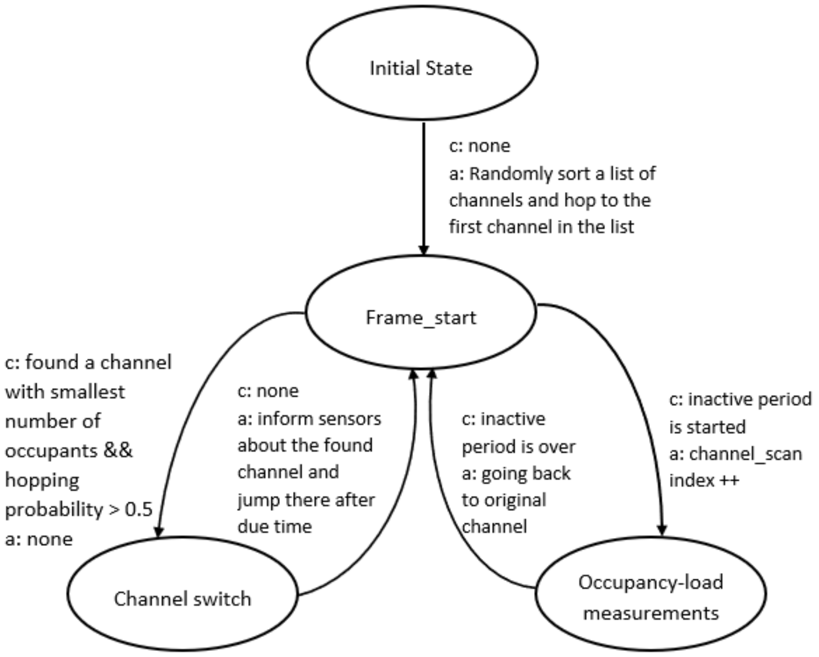

**Fig. 10** State machine diagram for the frequency-adaptation procedure in the DPS scheme

the collected time is multiplied with the average power consumption of that particular state.

$$P_i = C_i \times V_i \tag{3}$$

Where power consumed $P_i$ at a given transceiver equals to current drained from the battery $C_i$ at the specific state i, multiplied by the voltage of the battery $V_i$. This would help us to compute the total energy consumption. Energy consumption levels of both coordinators and sensors are individually measured and given in Joules. Note that we expect the coordinator energy consumption to be significantly larger for the dynamic schemes (i.e. dynamic-targeted-hopping and dynamic-phase-shifting) in which extra listening (scanning channels) occurs compared to other schemes. The listening state for the coordinator is as the same as the receiving state for both sensors and coordinators. While each sensor immediately goes to sleep after successful transmission of the collected data to its associated coordinator within the active period, the coordinator remains in its receiving mode (listening mode) to collect as many beacon packets as possible to determine the channel with the smallest occupants for the future frequency hopping if required. Moreover, the considered energy model does not take the size of different types of packet into account as the size variation of the generated data packets is the same (randomly selected between 64 bytes to 102 bytes with uniform distribution) and also the size of the beacon, acknowledgement and other control packets are fixed for all WBSNs. The main parameters used in our performance evaluation are summarized in Table 1.

### 4.1.3 Dynamic Environment

In this simulation experiment, a generic scenario (closer-to-reality) is considered in which WBSNs continuously and dynamically leave the frequency spectrum and start utilizing it after a while. We have accomplished this by continuously switching WBSNs off and on during the simulation time of 3000 seconds. More specifically, a WBSN switches off after a random time selected from [500BI, 1000BI] and switches back on after a random time selected from [400CAP, 600CAP]. Note that for switching back on the CAP period is used to make sure that the active phases (time slot) of all WBSNs will be shifted as well. When a WBSN switches back on, its operating frequency will also be determined randomly. Considering the Beacon Interval of 0.983 second and CAP duration of 0.245 seconds and the simulation time of 3000 seconds, switching a WBSN off after a randomly determined BI and switching it back on after a randomly-determined CAP and also probably in a different channel would highly-likely change the phase of that WBSN. Now when the phase changes occur for all WBSNs at random time frames, a dynamic the environment will be created in such a way that the previous random WBSN arrangement (in the same channel and also across the frequency spectrum) may no longer exist. Arguably, this would create a dynamic environment where an individual who carries a WBSN can experience the dynamic exposure to frequency interference coming from other WBSNs.

### 4.1.4 Performance Measures

This section explains the considered performance measures and its relevant terminologies. One of the terminologies that is quite often used in our performance measurements is the term *satisfaction*. A WBSN is regarded as *satisfied* if its average successful transmission of the data packets is 95% and above. Note that this value is 98% for DPS scheme as suggested by the outcome of the simulation study discussed earlier. Having defined a satisfied WBSN, the *satisfaction rate* would be the percentage of the satisfied WBSNs out of the total number of WBSNs. The satisfaction rate plays our first performance measure. Note, when a sensor node is orphaned, its generated data packets enters the sensor buffer and will be discarded after the buffer becomes full. The discarded packets are also counted as lost.

The second terminology (second performance measure) is *carrying capacity*. For an envisaged scheme, the carrying capacity is defined as the number of WBSNs that can be located at close proximity in such a way that at least 95% of them are satisfied. This performance measure indicates how efficiently the frequency spectrum can be utilised by employing either of the above-mentioned schemes. To calculate the carrying capacity, a given scheme is simulated where the number of active WBSNs $\delta \in \Delta$ and $\Delta = \{50, 100, 150, 200, 250\}$. For each $\delta \in \Delta$, a number of 64 simulation runs are carried out. For each simulation run, the number of satisfied WBSNs is calculated and, the average of these numbers over all replications attains us the average percentage of the satisfied WBSNs for the given $\delta$ WBSNs. When all the averages for all $\delta \in \Delta$ is calculated, a second-order polynomial regression curve is deployed to interpolate the average number of satisfied WBSNs between the given points in $\Delta$. Finally, the carrying capacity is calculated as the point where the regression curve crosses the 95% line.

The criticality and the importance of the sensor energy consumption have been discussed before, in this section. Thus the sensor energy consumption is also one of the performance measures. The *sensor energy consumption* is defined as the average energy consumption of all sensor devices of all WBSNs over all simulation runs. Similarly, the *coordinator energy consumption* is the average energy consumption of all coordinators over replications.

When a sensor nodes loses four consecutive beacon packets, it becomes orphan, or in other words, it enters to the orphan state. During this period, the packets will be stored in the sensor's buffer, and once the buffer is full, the upcoming packets will be discarded and counted as lost. The longer sensor spends time in the orphan state, the more packet loss will be experienced and eventually, lower satisfaction rate will be achieved. Additionally, an orphan sensor node has to scan the whole frequency spectrum (for adaptive frequency schemes), which results in spending more energy than usual. Therefore, the *fraction of time without PAN coordinator* (or orphan period for short) is also considered as one of our performance measures. This performance measure indicates the average fraction of time that the sensor nodes spend in the orphan state and is taken over all sensor nodes from all WBSNs.

### 4.2 Experimental study

The main goal of this study is to examine the feasibility of implementing the DPS scheme on real-world sensor devices (MIB250 boards). Due to limitation of the number sensor devices, only two sensor devices – a coordinator and a sensor – form a WBSN. A group of WBSNs $\delta \in \Delta$ and $\Delta = \{4, 7, 10, 14\}$ are equidistantly distributed on a circle with the diameter of 1 meter in such a way that the coordinator and the sensor of a WBSN are located at both ends of a diameter. This arrangement, along with the transmit power -15 dBm for both sensor and its respected coordinator of a WBSN results in exposing all WBSNs to experience mutual interference. Moreover, this arrangement maintains the originality of the IEEE 802.15.4 MAC protocol as well as eliminating the possibility of experiencing packet losses because of hidden-terminals, shadowing and path loss situations. Therefore, packet losses can be confidently attributed to packet collisions with packets transmitted from other WBSNs. Note that due to channel scarcity and a limited number of sensor devices, we have utilised

**Fig. 11** WBSNs arrangement in the experimental study

only one channel and decreased the number of WBSNs accordingly compared to a simulation study. Figure 11 shows the WBSNs arrangement.

To make sure that no other technologies utilise the same operating frequency and thus interfere with or experiment's obtained results, a spectrum analyser is located at the centre of the circle that monitors the technologies that utilise the frequency spectrum. The rest of parameter specifications are similar to values presented in table 1. Note that the functionality of static-random and DPS schemes are explained in simulation study section in detail.

### *4.2.1 Performance Measures*

To evaluate the performance of the considered schemes in the experimental study, a range of reliability-oriented performance metrics is considered and defined in the followings.

Number of beacon packet loss: This performance metric is the average total number of lost beacon packets for the monitored sensor nodes over all experimental runs.

Number of transmissions retries: When a sensor device transmits a data packet and does not receive the corresponding acknowledgement, it assumes that the data packet has been lost and attempts to re-transmits it again for a specific number of times. Therefore, the average total number of transmission retries over all experimental runs is also considered as one of the performance metrics.

Number of data packet loss: Data packet losses are calculated via counting the gap between two consecutive data packets at the coordinator side. The average of total data packet losses over all experimental runs is considered as the number of data packet loss.

Duration of time spent in the orphan state: How a sensor device enters the orphan period has been discussed earlier. The average total amount of time spent in the orphan state over all experimental runs is also considered as a performance metric.

#### *4.2.2 Experimental Scenario*

In each experimental run, the $\delta$ number of WBSNs is increased according to $\Delta = \{4, 7, 10, 14\}$ in a step-wise fashion. Each step lasts to 15 minutes. Once the maximum number of WBSNs ($\delta = 14$) is reached, the number of WBSNs is step-by-step decreased to the smallest number of WBSNs $\delta = 4$. This scenario repeatedly takes place for the minimum of 10 experimental runs. In each experimental run, the performance of WBSNs is measured using the performance metrics explained earlier.

## **5 Results and Discussion**

The obtained results of both simulation and experimental studies are shown and discussed in this section.

### 5.1 Simulation Results

This section discusses the performance of WBSNs in a dynamic environment under the influence of mutual interference. A simulation study is conducted in order to evaluate the schemes described above. We have used an open-source network simulator designed for WBSNs simulation scenarios called "Castalia 3.2“ [1] and [23]. Each simulation run lasted for 3000 seconds, which on average corresponds to at least 3,000 packets generated by each sensor node. Furthermore, for each parameter setting ($\Delta$) and each proposed scheme, we have run at least 64 replications. Further replications are added as needed to achieve a relative confidence interval half-width not larger than 5% at a 95% confidence level, for the success rate.

As a reminder, the static-random scheme was introduced as the benchmark in which WBSNs are uniformly distributed over 16 available operating frequencies. This scheme closely follows the MAC protocol offered in IEEE 802.15.4 standard protocol. The static-initial-choice scheme, however, enabled WBSNs to scan the whole frequency spectrum once and select the operating frequency with the smallest number of occupants. The results indicate small improvements in satisfaction rate, the energy consumption of sensor nodes and the carrying capacity. Such improvements are obtained as a result of choosing an operating frequency with the smallest number of occupants. This strategy would eventually lead to better distribution of WBSNs across the 16 available operating frequencies at the early (initial-choice) stage of WBSN's activation.

In the next step, WBSNs are equipped with the capability of adaptively switching to other operating frequencies either randomly or after performing some measurements. The proposed dynamic schemes (i.e. dynamic-targeted and dynamic-random scheme) that employed frequency adaptation strategy presented significant improvements of satisfaction rate, carrying capacity and lesser sensor energy consumption compared to both static-random and static-initial-choice schemes. Such significant improvements are achieved as a result of switching to another operating frequency when the successful transmission of data packets degraded below the threshold. The future operating frequency is determined either randomly (dynamic-random-hopping scheme) or using the result of a measurement scheme which determines an operating frequency with smallest number of occupants (dynamic-targeted-hopping). The obtained results indicate that switching to an operating frequency with the smallest number of occupants presumably distributes WBSNs evenly across all 16 available operating frequencies along with experiencing lower ratio of overlapping active periods of WBSNs in that operating frequency.

The results obtained from the above-mentioned schemes has highlighted the fact that to achieve higher satisfaction rate, a WBSN must be able to adaptively hop to another operating frequency whenever its successful transmission of data packets dropped below a certain threshold. This frequency adaptation strategy is beneficial in such a way that it provides a WBSN with an opportunity to escape from currently experiencing "active period overlapping" situation and resuming the activities in another operating frequency. However, switching to another operating frequency does not guarantee to switch to a free time slot. A WBSN might still experience overlapping of active periods, which lead to beacon collision and eventually, performance degradation. To overcome this issue, DPS scheme is proposed in which a WBSN not only switches to another operating frequency, but also it is programmed to switch to other phases (time slots) while utilising an operating frequency. Both frequency adaptation and phase shifting adaptation strategies are performed in parallel with minimum interactions and dependencies between them. The obtained results clearly show that the capability of switching to other phases has significantly improved the satisfaction rate and carrying capacity as well as decreasing sensor's energy consumption. Figures 12 to 15 depict the performance trends of WBSNs in terms of satisfaction rate, sensor orphan time and energy consumption of both sensors and coordinators when employing the above-mentioned schemes.

The comparison between the DPS scheme and the static-random scheme reveals that the combination of frequency and phase adaptation scheme has improved WBSN's satisfaction rate by over 50% when the total number of 250 WBSNs are distributed across 16 available operating frequencies. This is mainly due to decreasing the overlapping ratio of WBSNs active periods. Lower ratio of overlapping active periods results in lesser packet collisions which in

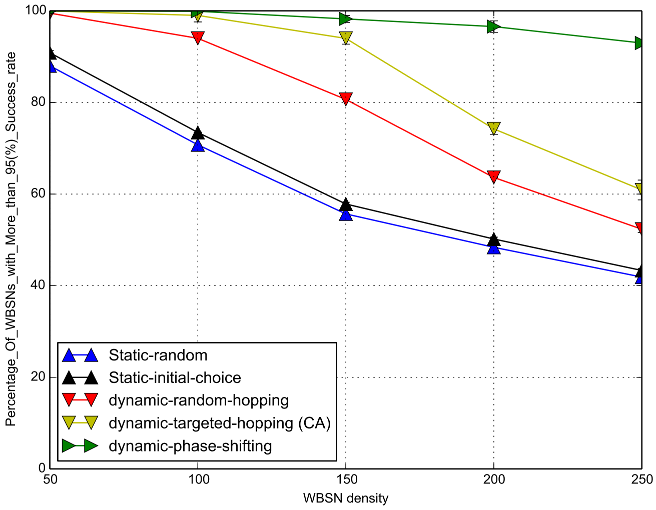

**Fig. 12** On average satisfaction rate in a dynamic environment

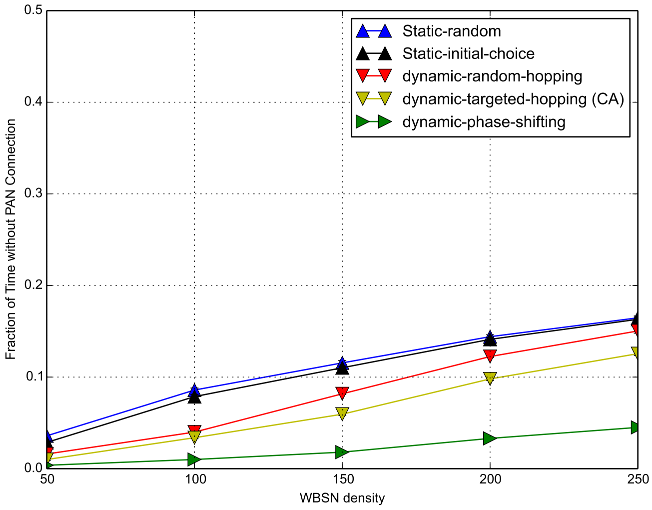

**Fig. 13** Average fraction of Time without PAN Coordinator in a dynamic environment

**Table 2** Carrying capacity presented by the considered schemes in a dynamic environment

| Scheme | Carrying capacity |
|---|---|
| static-random | 20 |
| static-initial-choice | 23 |
| dynamic-random-hopping | 94 |
| dynamic-targeted-hopping (CA) | 141 |
| dynamic-phase-shifting | 225 |

turns leads to experiencing lower packet loss rate (or higher successful transmission of data packets) and eventually, higher satisfaction rate. Previously, it has been mentioned that coordinators do not perform “clear channel assessment” before transmission of beacon packets at the beginning of every superframe. Therefore, the higher ratio of overlapping active periods would highly likely result in experiencing beacon packet collisions. Sensors that do not receive four consecutive beacon packets enter to orphan state and their collected data will be buffered. Once the sensor buffer becomes full, the upcoming receiving data packets will be discarded and will be counted as lost. Figure 13 shows the fraction of time that sensor devices, on average, spent in the orphan state has been improved significantly for DPS scheme compared to the static-random scheme in a dynamic environment. An orphaned sensor device attempts to re-associate itself with its respected coordinator. This extra energy-consuming activity is tightly bundled with the nature of an employed scheme. For static schemes, the orphaned sensor device has to only scan the current channel to find its corresponding coordinator. However, for dynamic schemes, the orphan sensor device assumes that the coordinator has hopped to another operating frequency which requires scanning all available operating frequencies to find its coordinator. This significantly increases the sensor’s energy consumption for dynamic schemes. Coordinator’s energy consumption in dynamic schemes is significantly higher than static schemes. This is mainly due to the fact that the coordinator constantly keeps track of the quality of the current and other operating frequencies, so the WBSN is always ready to hop to another operating frequency if required. Obviously, constantly measuring the quality of operating frequencies has improved the satisfaction rate and lowered the sensor energy consumption but at a higher price of coordinator’s energy consumption. Figures 14 and 15 present the average sensor and coordinator energy consumption.

Carrying capacity is another performance measure which is defined as the number of WBSNs that can be located at close proximity in such a way that at least 95% of them are satisfied. Table 2 shows as the total number of WBSNs becomes larger in the frequency spectrum, the carrying capacity for schemes other than DPS scheme becomes significantly smaller. More specifically, by comparing the carrying capacity of the static-random and the DPS scheme in a dynamic environment, it can be observed that only 20 out of 250 WBSNs experience 95% and above successful transmission of data packets, whereas this number for DPS scheme is 225 out of 250 WBSNs.

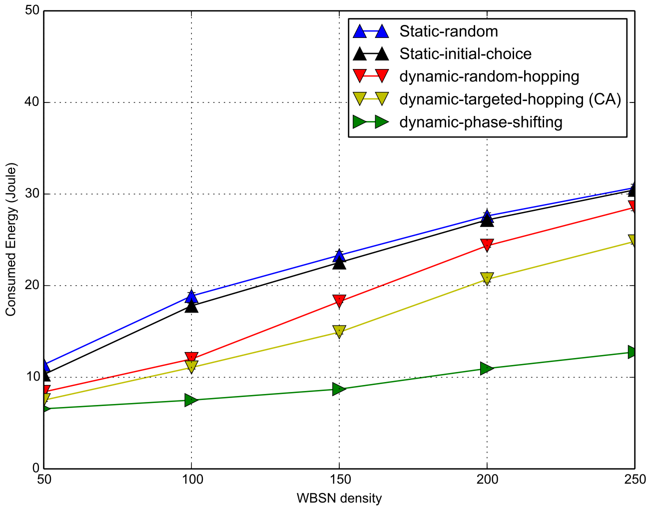

**Fig. 14** On average sensor Energy Consumption in a dynamic environment

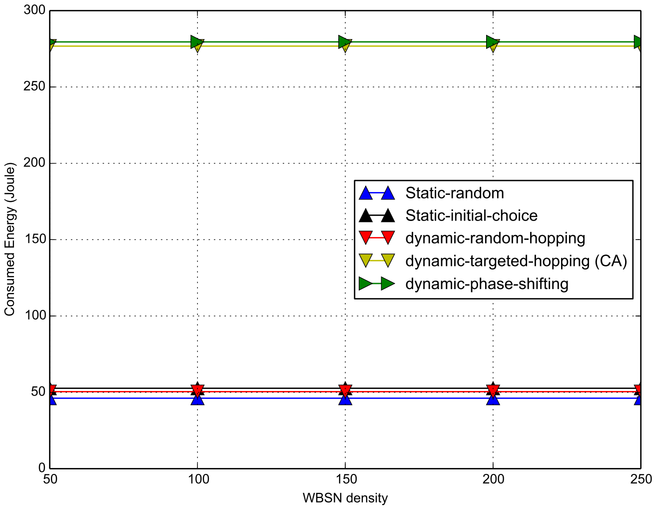

**Fig. 15** On average coordinator Energy Consumption in a dynamic environment

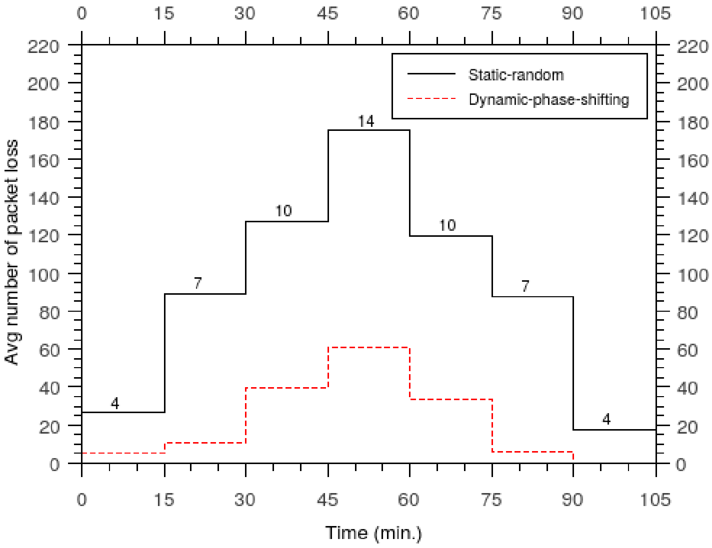

**Fig. 16** Average total number of data packet loss

### 5.2 Experimental Results

The performance trends of both DPS and static-random schemes are explained in this subsection. As the number of WBSNs becomes larger in an operating frequency, a larger portion of the active periods overlaps on each other. Consequently, a larger number of packet collisions would be experienced, and eventually, the performance of WBSNs would degrade significantly. Figures 16 and 17 illustrate the average total number of lost data and beacon packets, respectively, over all experimental runs as the number of WBSNs is increased and decreased in a step-wise fashion.

As mentioned earlier, when a sensor device does not receive the acknowledgement corresponding to the sent packet (due to packet collisions), it re-transmits the data packet up to a certain number of retries. Figure 18 shows the average total number of re-transmitted data packets over all experimental runs in a step-wise fashion described earlier. Moreover, a sensor device that did not receive four consecutive beacon packets (due to packet collisions) enters to the orphan state and data packets stack up in the sensor device's buffer and will be discarded, thereafter. Figure 19 shows the average total amount of time spent in the orphan state over all experimental runs for both static-and DPS schemes.

The ability to shift to other phases in the DPS scheme provides WBSNs with an opportunity of shifting to another phase (time slots) whenever the successful transmission of data packets dropped below the threshold. Therefore, a smaller number of data packet and beacon packet losses is obtained

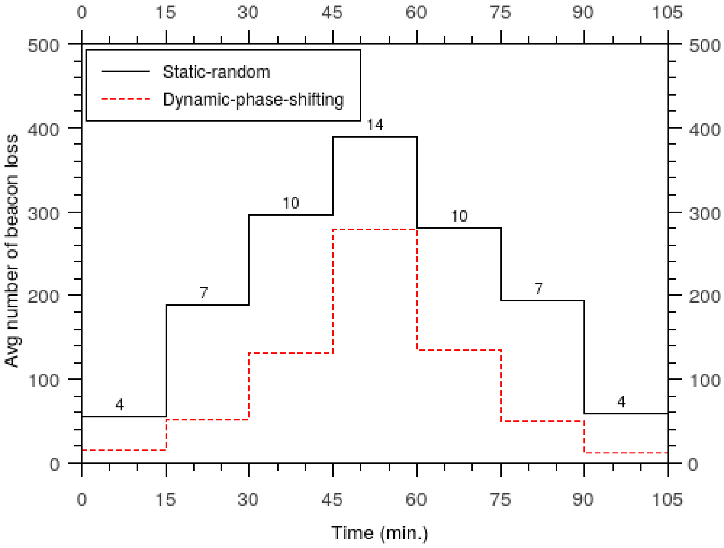

**Fig. 17** Average total number of beacon packet loss

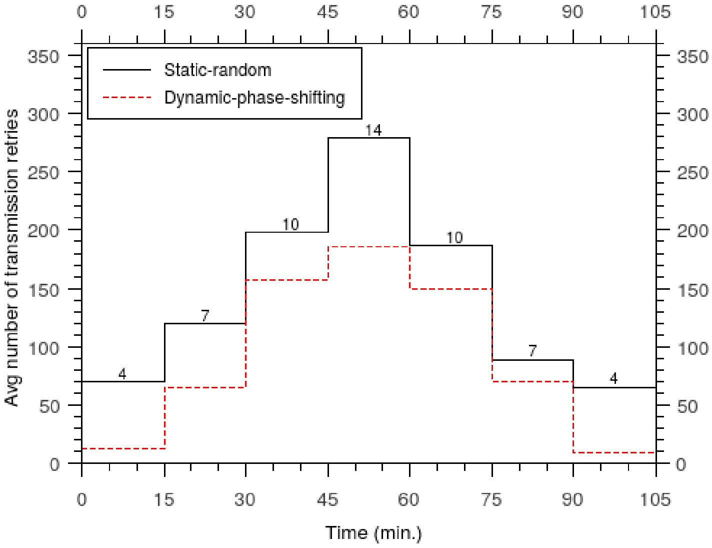

**Fig. 18** Average total number of transmission retries

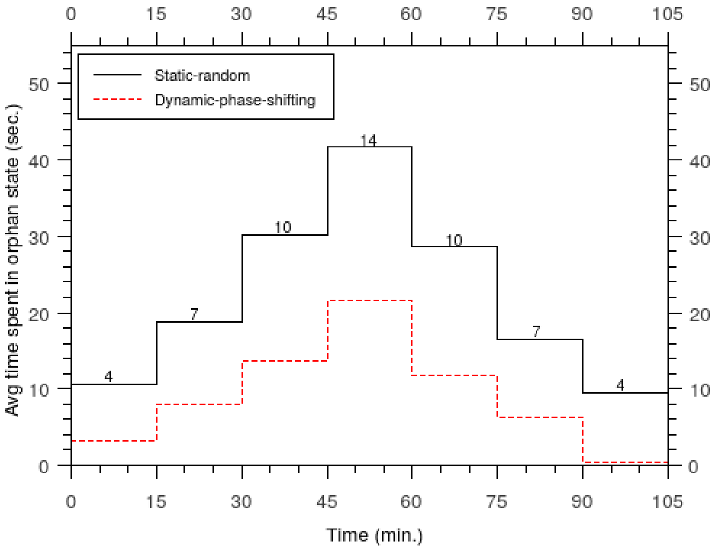

**Fig. 19** Average total amount of time spent in the orphan state

in the DPS scheme compared to the static-random scheme. Furthermore, the ability to shift to other phases in the DPS scheme has resulted in fewer packet collisions, a smaller number of transmission retries and shorter amount of time spent in the orphan state compared to static-random scheme. Note that the frequency adaptation approach has been disabled for the DPS scheme in the experimental study as only one operating frequency has been utilised. More specifically, the obtained performance trends for the DPS scheme in the experimental study only illustrate the functionality of the phase-shifting adaptation approach compared to a scheme that closely follows the functionality of the IEEE 802.15.4 MAC protocol standard.

## 6 Conclusion

In this paper, we discussed mutual frequency interference imposed by neighboring WBSNs on each other in a dynamic environment where a large number of WBSNs continuously and randomly switch on and off utilising 2.4 GHz frequency spectrum. Mutual interference is mainly caused by packet collisions when the active periods of multiple WBSN overlap on each other. As the number of WBSNs becomes larger in an operating frequency, the higher overlapping ratio of active periods is inevitable. As a result, a larger amount of packet collisions will be experienced that negatively influences the successful transmission of packets as well as sensor energy consumption. To eliminate the destructive impacts of mutual interference, a number of schemes are proposed, and their performances have been evaluated in terms of transmission reliability and sensor energy consumption. The proposed schemes were identified as static (i.e. static-random and static-initial-choice) and dynamic schemes (dynamic-random-hopping and dynamic-targeted-hopping), where terms static and dynamic refer to the capability of switching to other operating frequencies whenever required. The frequency adaptation strategy has significantly improved the reliability of packet transmission as well as lowering the sensor energy consumption. However, switching to another channel does not guarantee hopping on a free time slot. Therefore, a scheme (i.e. dynamic-phase-shifting) is proposed in which WBSNs could change their phases (time slots) in an operating frequency as well as switching to other operating frequencies whenever required. The results have shown that the combination of frequency and phase adaptation strategy significantly outperforms both frequency adaptation and static approaches in a dynamic environment. In our future work, we plan to expose DPS scheme to external interference and determine its performance along with making necessary changes to its functionality to achieve high reliability of data packet transmissions as well as low energy consumption for WBSNs.

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