Evaluation of DECT-ULE for Robust Communication in Dense Wireless Sensor Networks

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Abstract—**In today's world wireless sensor networks (WSNs) have enormous applications which made our everyday life much easier. In most of these applications, the unlicensed 2.4 GHz frequency band has been used for sensor communications. Due to the wide use, the chance of getting interference in this frequency band is quite high. Thus, a reliable and real-time communication in mass WSNs can not be guaranteed, which is essential for industrial applications. In this paper, we evaluate the performance of Digital Enhanced Cordless Telecommunications - Ultra Low Energy (DECT-ULE) for robust communication in dense WSNs and found that it can cope with the limitations of existing standards. We show that DECT-ULE can elegantly handle dense WSNs by allocating communication channels with excellent quality and minimum delay.**

I. INTRODUCTION

WSNs have been widely implemented in a lot of applications such as home automation [1], wild life monitoring [2], industrial control [3], health care [4], under water research [5], etc. In spite of having different objectives, successful communication between different sensors and base stations is the most important issue in all of these cases. Due to the tiny size and limited battery life, the transmission power of wireless sensors is usually low, which results in a short transmission range. Eventually, WSNs require a dense deployment which helps to increase the network range by making mesh networks. Typically, several messages have to be exchanged between multiple nodes to transmit a data packet successfully from a source to a destination in such a mesh network. This takes a couple of frames. So, the latency of communication in WSNs becomes high. In addition, multi-hop routing algorithms are essential to efficiently select the nodes for packet delivery in a mesh network. High weight communication algorithms are also required to increase the system reliability in this case. This consumes high energy that quickly drains the battery life of the wireless sensors and make the overall situation challenging.

Recent developments in ubiquitous computing require robust and reliable WSNs for industrial applications where real-time communications are essential. In this work, we consider a such high density industrial WSN with diverse traffic patterns. Several communication standards such as WirelessHART, ISA 100.11a, ZigBee etc., have been designed in past to support industrial WSNs. WirelessHART and ISA 100.11a can support maximum 50-100 devices in a network [6]. However, thousands of sensors should to be supported in modern industrial networks. Thus, interference becomes a major issue here. The radio resources have to be shared intelligently among different users by enabling multi-channel communications to solve this issue [7]. Again, all of these above mentioned standards use the low power IEEE 802.15.4 radio interface for communications [8]. So, the sensors have to make a mesh network to communicate with the base stations. A typical packet delivery takes few hundred milliseconds in a network which uses WirelessHART or ISA 100.11a. The physical (PHY) layer of IEEE 802.15.4 uses the unlicensed 2.4 GHz frequency band which is also used by many other devices in homes and offices such as, WiFi, bluetooth devices, microwave ovens etc. As a result, communication channels in this band encounter interference not only from its own system but also from other neighboring devices operating in the same band. So, the chance of having interference in this band is quite high. The IEEE 802.15.4 standard is designed for low and medium data rate (maximum raw data rate of 250 kbps) applications. For delay tolerant sensor network applications, the properties of IEEE 802.15.4 standard are still suitable. However, bad communication channels due to interference, large packet delivery time and low data rate are not acceptable in many industrial applications. Thus, the standards based on IEEE 802.15.4 can not fulfill the requirements of our scenario, such problems have been addressed in [9]. Some attempts also been made to use WiFi (IEEE 802.11) for sensors networks. Despite providing high data rate, WiFi doesn't considered as a suitable technology for industrial applications due to its high power consumption and lack of communication reliability which is common in carrier sense multiple access (CSMA) systems [10]. As a consequence, modern industrial WSNs stand in need of a standard which can provide robust and real-time communications with sufficiently long transmission range, high throughput and low energy consumption. DECT-ULE which is the energy efficient version of DECT standard, gives the impression to cope with these demanding situations.

DECT is a digital communication standard developed by the European Telecommunications Standards Institute (ETSI) in early 1988. It is seen as a power hungry communication standard which is primarily used for cordless phones. Recently developed low energy version of DECT (DECT-ULE) seems to provide prominent services for industrial sensor networks. Table I shows a comparison of basic performance parameters between DECT and other technologies presently used in WSNs. Many works have been done to evaluate

Table I
PERFORMANCE PARAMETER COMPARISON OF DECT WITH OTHER TECHNOLOGIES.

Radio technology	Operating frequency band	MAC-DLL mechanism	Range	Channel bandwidth	Supported number of devices	Maximum data rate	Modulation	Network architecture
WirelessHART	2400-2483.5 MHz	Channel hopping, blacklisting, TDMA	Indoors: 30m Outdoors: 90m	2 MHz	Hundred	250kbps	O-QPSK, DSSS	Star, Mesh
ISA 100.11a	2400-2483.5 MHz	CSMA/CA, channel hopping, blacklisting, superframe optimization	Indoors: 30m Outdoors: 90m	2 MHz	Hundreds	250kbps	O-QPSK, DSSS	Star, Mesh
ZigBee	868-868.6[a], 902-928[b], 2400-2483.5 MHz	CSMA/CA, beacon synchronization	Indoors: 30m Outdoors: 90m	0.6[c], 1.2[d], 2[e] MHz	Thousands	20[c], 40[d], 250[e] kbps	BPSK[c,d], O-QPSK[e], DSSS[e]	Tree, Star, Mesh
WiFi	2400–2483.5[g,h,i], 5150-5825[f] MHz	CSMA	Indoors: 33m Outdoors: 95m	20[f,h,i], 22[g,h], 40[i] MHz	Hundreds	11[g], 54[f,h], 150[i] Mbps	DSSS[g,h], OFDM[f,h,i]	Mesh
DECT	1880-1900 MHz	DCS, FDMA, TDMA-TDD	Indoors: 75m Outdoors: 300m	1.728 MHz	Thousands	1.152 Mbps	GFSK	Star, Tree

[a]Only allowed in Europe; [b]only allowed in North America; [c]in case of 868 MHz channel; [d]in case of 915 MHz channel; [e]in case of 2450 MHz channel; [f]in case of IEEE 802.11a; [g]in case of IEEE 802.11b; [h]in case of IEEE 802.11g; [i]in case of IEEE 802.11n.

the performance of DECT for cordless voice communications by analyzing the dynamic channel selection (DCS) algorithm which is explained in Section II-B [11]–[16]. However, to the best of our knowledge no work is accomplished to evaluate DECT for WSNs. In this paper, we analyze the performance of DECT-ULE in a dense WSN environment under different setups. The main contributions of this paper are as follows:

- We evaluate the quality of the channels used in sensor communications by calculating the signal to interference and noise ratio (SINR) under different conditions;
- We quantify the channel selection failure probability of DECT-ULE in a dense WSN and check whether the sensor data is retrievable or not;
- We check the latency of communication (i.e., the delay to establish a connection);
- We analyze the overall performance of the network under different traffic (low and high) densities.

The rest of the paper is organized as follows. In Section II, we briefly explain the features and operating principles of DECT, in Section III, we introduce the simulation environment and formulate the problem, the results are explained in Section IV, and finally we conclude this paper mentioning future research plans in Section V.

II. FEATURES AND OPERATING PRINCIPLES OF DECT

In Europe, DECT PHY layer occupies the licensed and royalty free block of radio spectrum from 1880 MHz to 1900 MHz.[1] DECT has a centralized system, where the fixed part (FP) provides wireless communication to the portable parts (PPs) by broadcasting beacons containing system and access right information. An FP may comprises several radio fixed parts (RFPs). The RFPs are typically connected between themselves through wires that maintain high synchronization. DECT divides its bandwidth in 10 radio carriers using the frequency division multiple access (FDMA). Again, the time division multiple access-time division duplex (TDMA-TDD) structure provides 12 time slots for up-link and 12 time slots for down-link per carrier with a frame duration of 10 ms. As a result, DECT has 240 physical channels for communication. However, an RFP/base station with single transceiver can only handle 12 simultaneous call as the radio can not switch between frequencies in a particular time slot [17]. A typical DECT frame on an RFP is shown in Figure 1, where the RFP is busy on 2 channels (marked in Blue and Green colors). The RFP cannot communicate on the channels marked in Grey color which are so-called blind channels. The channels marked in White color are the free channels on that RFP.

DECT system uses bearers to provide connection-oriented and connection-less services. The MAC layer of DECT creates bearers from the data packets it sends and receives from the PHY layer. DECT uses four different types of bearers, those are simplex, duplex, double simplex, double duplex. If a single slot in PHY layer is allocated for a service, the bearer is called simplex bearer. The bearer where one slot in down-link and another in up-link have been allocated for a service is known as duplex bearer. These two slots are allocated in the same RF carrier with 12 slots spacing in between. This type of bearers are used in DECT voice communication most frequently. Double simplex bearers have the same structure as duplex bearers except the both slots are used in the same direction, i.e., either in down-link or in up-link. This type of bearers are usually used for data streaming from base stations to the mobiles and vice versa. These bearers have to be guided by a duplex pilot bearer. Double duplex bearers is

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[1] In the rest of the world it has different frequency band based on location.

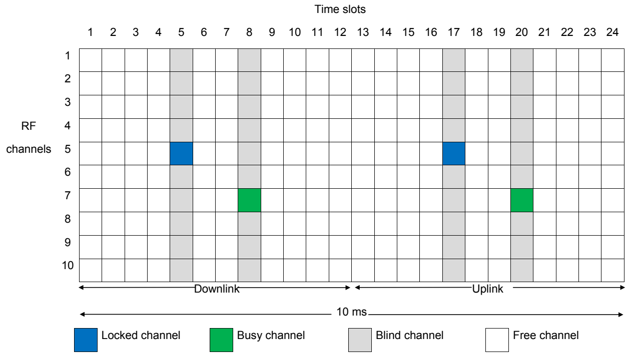

Figure 1. DECT frequency/time spectrum

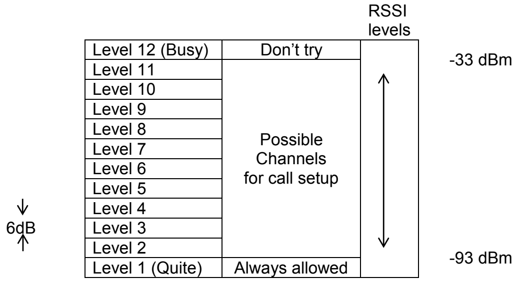

Figure 2. Channel selection list

a combination of two duplex bearers in two RF carriers [18].

A single DECT RFP can support hundreds of PPs. So by using tens of those, thousands of PPs can be supported in a network. The data rate of DECT is much higher than those of WirelessHART, ISA 100.11a or ZigBee. The raw data rate of DECT is 1152 kbps, which is suitable for data streaming as well as for low data rate applications. DECT also provides long radio range (typically up to 75m indoors and up to 300m outdoors) due to the permission of high transmission power. Complex mesh networking thus can be avoided, even if the network is large and dense. DECT-ULE is the *new version* of DECT which has low energy consumption due to its capability to go into long sleep mode without losing synchronization. Thus a DECT-ULE radio attached on a sensor can operate years (typically 5-10 years) on a single battery. In standby mode, a DECT-ULE chip draws about 5 mA current at 3.3 V power supply. As, all the features of DECT-ULE are almost same as those of DECT, the results obtained in this paper using DECT-ULE will be same with DECT also, unless mentioned.

The operating principle of DECT is briefly explained below.

A. Fixed part beacon and the portable locking procedure

Every radio network from a single cell to multi-cell system, broadcasts beacons to provide the PPs not only the access right information but also the system information, paging information, etc. To place the beacons, FPs have to select suitable channels. The FPs and PPs in DECT system maintain the same protocol for channel selection, *"listen before transmit"*. After powered on, RFPs scan the physical channels to create a list of least interfered channels. The channels on which the RFP receives low RSSI or can't detect anything are known as least interfered channels. The RFPs then place their beacons on one of those. These channels are known as locked channel. In Figure 1, the corresponding RFP broadcasts its beacons on RF carrier 5 and slot 5 marked in Blue color. The PPs have to listen to the RFPs on one of the locked channels to get locked in the system. In DECT, every RFP broadcasts at least one beacon in each frame. As a large amount of information is suppose to broadcast throughout the network using the beacon, this information is divided into several parts and is broadcasted in several frames. As a result, the contents of the beacons of a particular RFP at every frame may not be identical. The MAC layer of DECT controls this multiplexing, the details are beyond the scope of this paper [17].

In DECT, 16 frames create a multiframe (frame number 0 till 15). Among many other information, the access right information is placed in every frame while the system information is only broadcasted in frame 8 of a multiframe. When a PP has been switched on, it tries to receive a beacon from the FP. If beacons from several RFPs have been received by a PP, it selects the beacon of the RFP from which it gets the strongest received signal strength indicator (RSSI). The PP then checks the access right information to determine whether or not it has an access on that system. If the PP can decode the access right information successfully, several messages are exchanged to lock the PP into the system. After receiving the system information from the beacon the PP can achieve the multiframe synchronization as this information is only placed in frame 8 of a multiframe.

The RFPs change the channel for beacon broadcast in a regular interval even if there is no interference. In frame 8 of every multiframe, the FP declares selected the RF carrier and slot number of future locked channel for next multiframe. So, the PPs have been notified about any change in locked channel beforehand. This enables the PPs to switch the locked channel without loosing the synchronization.

B. Dynamic channel selection (DCS) and call setup

The PPs drive the call setup, handover and many other major protocols of communication in DECT standard, which is unique among other communication standards. To select the best channel for call setup, all the PPs in the DECT system keep a list of suitable channels which is updated periodically. To create this list, PPs are listening to the RFPs on the free channels constantly when on active calls and occasionally when idle.[2] The channels in which the PPs receive high RSSI are considered busy and the channels in which the PPs don't receive anything are the quietest channels. According to the

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[2] Free channels on a PP mean the channels in which the PP is not communicating with an RFP in a particular frame.

RSSI, the PPs sort the channels into 12 levels. Level 1 contains the least interfered channels, i.e. the channel whose RSSI is less than the receiver sensitivity (typically -93dBm) and level 12 contains channels whose RSSI is greater than -33dBm. As the channels in level 12 are the most interfered ones and no call should be requested on those channels. All other channels are sorted into 10 levels in between with 6 dB interval. A typical channel selection list on a PP is shown in Figure 2. If a PP wants to initiate a call in a system on which it has granted access beforehand, at first it selects the strongest RFP.[3] Then it requests for a connection on a channel from level 1. In case of channel unavailability in level 1 other channels in higher levels up to level 11 can be tried to make a connection in a hierarchical order. After selecting a channel, the PP has to check the RSSI of that channel in next two frames before finally selects the channel for call setup. If the RSSI of the channel doesn't decrease 12 dB from the initial value, the PP sends a call request on that channel. The RFP assigns the channel straight forward if it is free. It may happen that more than one PPs requested for a connection on the same channel, so a collision may occur at the receiver of the RFP. In this case no PPs may get an acknowledgment from the RFP, so the PPs have to select another channel for the call. The phenomena when a PP places a call request on a channel but the channel can not be allocated is known as *channel selection failure* [19]. In case of channel selection failure, the PPs may try another 5 suitable channels in the same RFP to setup the call, if failed the next two strongest RFPs can be tried using the same procedure. If no connection can be made after trying 3 strongest RFPs, the call will be *dropped* [20].

Again, in case an RFP doesn't have any free channels to accept further call requests, the RFP can send this information on its beacon. Then the PPs belong to that RFP know that the RFP is unable to take further call requests even though that is the strongest RFP for those PPs. However, in that case the PPs under question can direct their call requests to the respective 2nd strongest RFP instead.

C. Paging

If the FP wants to call a PP (usually a call has always been initiated by the PPs in DECT system) it sends paging messages over the beacon throughout the network. The PP in question is then know that there is a call waiting for it. The paging information is typically placed in frame 0 of a multiframe. By doing so the PPs only need to wake up once in every multiframe to check for incoming calls after getting locked into the system [18]. This helps the PPs to save energy. In case of DECT-ULE the PPs can go into sleep mode for a longer period (up to 20 seconds) than the allowed maximum sleep time in original DECT (1 to 4 multiframe duration, i.e., 160 milliseconds to 640 milliseconds). However, this will increase the latency. During this long sleep period, the DECT-ULE chip draws a very small amount of current (typically 3 μA, maximum 5 μA) which enables the wireless sensors to last for years on a single battery [21]. An external clock is used in DECT-ULE chip to trigger a force wake-up if necessary. This allows the PPs to react fast and communicate with the FP in case of emergency.

If there are a lot of paging in the system, the paging information can also be placed in the even numbered frames. In those cases, this is notified through the beacon of previous even numbered frame. So, the PPs know in advance that they have to awake again in next even numbered frame to check for the incoming calls. A connection has only been made if the PP accepts the request, if not the call will be abandoned. In practical systems paging information is generally broadcasted 3 times, this reduces the chance of missing a call by the PPs. The connection can be ended by placing call releasing bearers when either parties (PPs) press the end button .

D. Call supervision and handover

During a call each PP monitors the RSSI from all RFPs, the RSSI on each channels and the communication quality (i.e., message error rate) on both up-link and down-link. If at the time this monitoring, the PP finds another RFP whose RSSI is at least 10 dB higher than that of the present RFP, it initiates a handover procedure. The handover procedure is similar to the call setup procedure except the PP maintains two simultaneous connections during the handover procedure [20].

Any signal whose power is greater than the receiver sensitivity can be detected by a receiver. Nevertheless, a minimum SINR should be maintained to successfully decode a received signal. The interference in DECT mainly occurs due to the use of same channel by different pairs of RFP and PP, which are in the communication range of one another. The interference is calculated on a PP for a particular channel by summing up the received power from two other RFPs (if there are any) [22]. The PPs continuously check the SINR of the channels on which they are communicating. If a particular link becomes bad, the PP initiates a handover process. Most of the time, the handover has been done seamlessly.

III. PROBLEM FORMULATION AND SIMULATION SETUP

The nature of WSNs is quite different than telecommunication networks. It varies in geometry, density, traffic, call duration, data size, etc. Deployment of wireless sensors typically depends on the application. Most of the times, sensor nodes are dropped in an adhoc manner. In this paper, we consider a dense WSN in a car manufacturing industry where different types of sensors are deployed to gather different data and to control different machinery. Some sensors are employed to monitor the vibration signatures of different machines and control those wirelessly, some sensors collect the temperature readings, some sense the pressure, some control the lighting, etc.. In our network 25 RFPs are placed systematically in a 100 m X 100 m area and 1000 sensors are distributed uniformly throughout the area as shown in Figure 3. The sensors are equipped with radios and capable to communicate wirelessly with the RFPs. The physical connection through wires provides the RFPs high

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[3] The RFP from which it receives the beacon with the highest RSSI.

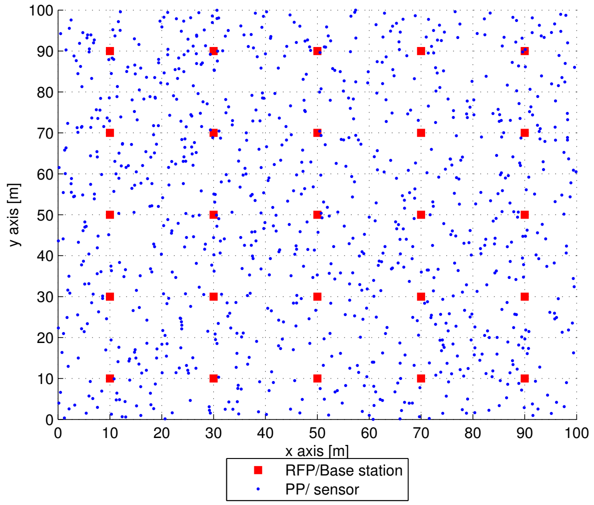

Figure 3. DECT WSN

synchronization, while the sensors get synchronize through the beacons.

In DECT systems intended for voice communication, the call generation is usually modeled according to Poisson's distribution. When a voice call has been initiated, it is expected to last for a while (typically, few minutes). The call duration in such networks is modeled as an exponential distribution by the researchers in [16], [23]. On the other hand, in sensor networks, the call generation pattern can be very diverse. Some sensors only initiate a call if those detect an event, while others are expected to send a message in a regular interval. Most frequently, the sensor data consists a few bytes so the call duration is quite small (typically 2 DECT frame duration).[4] However, applications where sensors are deployed to stream a large amount of data, the call duration can be high as voice call duration. As a result, the conventional models of call generation and call duration may not be suitable here. Up to 40 Bytes of user data can accommodate in one physical channel of a DECT frame, which allows maximum throughput of 32 kbps [17], [18]. So to support high throughput, more than one time slot allocation may be necessary for a particular communication link.[5] Therefore, to cope with these scenarios, we introduced three parameters: *the number of initiated calls in every frame*, N_c; *the duration of the call,* T_c and *the data size of the call,* D_c (i.e., the number of slots required in each frame for the call as this is directly related to the required throughput).

Before initiating a call, each sensor has to be locked into the DECT system through a suitable RFP from which it receives beacons with the highest RSSI. Suppose, $N_c \sim \mathcal{U}(0,n)$ calls can be initiated in the network at a particular frame. These calls are generated from different sensors, among which some may request a channel to the same RFP. In this paper, we evaluate the performance of DECT under different traffic density. The commonly used unit of traffic density, Erlangs to evaluate the performance of voice communication networks, doesn't make clear sense in case of WSN simulation. Thus, we choose numerical scale to simulate low and high call traffic (i.e., by varying the value of n in the distribution $\mathcal{U}(0,n)$) instead of using Erlangs scale. $n = 10$ has been set to simulate a low traffic network, while $n = 100$ has been set to simulate the high traffic case. The sensors have to select a channel which is relatively quite to place a call. For this purpose, DECT standard uses the DCS mechanism explained in the Section II-B. We also consider the *channel selection list* of the sensors (PPs) be updated in every 10 seconds (i.e, 1000 frames)[6]. To provide a diverse nature in call duration, we consider T_c (expressed in DECT frame duration) as a random integer generated from the following probability distributions,

$$\begin{aligned}
&P(T_c = T_{c1}) = 0.8;\ T_{c1} = 2\\
&P(T_c = T_{c2}) = 0.15;\ T_{c2} \sim \mathcal{U}(3,10)\\
&P(T_c = T_{c3}) = 0.03;\ T_{c3} \sim \mathcal{U}(11,20)\\
&P(T_c = T_{c4}) = 0.02;\ T_{c4} \sim \mathcal{U}(21,50)\,.
\end{aligned}$$

Again, the data size of the calls, D_c (required number of slots in a DECT frame) is also considered as a random integer created from the following distributions,

$$\begin{aligned}
&P(D_c = D_{c1}) = 0.95;\ D_{c1} = 1\\
&P(D_c = D_{c2}) = 0.05;\ D_{c2} \sim \mathcal{U}(2,6)\,.
\end{aligned}$$

In our simulation, we consider allocating duplex bearers for the calls whose data size requirement is below 7 slots and for the rest of the calls we allocate simplex bearers. We also introduce *periodic call generations* in the network as most of the sensors in WSNs are deployed to send a message in a regular interval. If sensor x_i initiates a call in frame p and the period of reporting is q frames, then sensor x_i will attempt for a call again in frames $p+q$, $p+2q$, $\cdots$. If a call from sensor x_i which is initiated in frame p is dropped after following the call setup procedure mentioned in Section II-B, the data size will be increased during the next expected attempt (i.e, during frame $p+q$) as the sensor has to send the old data also. This pattern will continue until the data size is equal to the maximum allowable slots in a base station. After that, the call will be dropped permanently as it is not possible to place such a call. As a consequence, the corresponding data can not be recovered. We define this phenomena as *lost call*. According to DECT standard, maximum 24 slots (22 simplex bearers guided by a duplex pilot bearer) can be allocated for a particular call.

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[4] For simplicity we represent the call duration with DECT frame duration.

[5] In this work we assume that 1 slot is necessary to support a throughput 0-32kbps, 2 slots are necessary to support a throughput 32-64kbps, and so on.

[6] The reduction in channel update time might increase the power consumption.

Propagation model

Every radio signals suffer from free space path loss, shadowing and fading during their travel from transmitter to receiver. These parameters depend on many things such as the geometry of the network, Doppler effect, etc. A correct propagation model is thus necessary to calculate the SINR of a channel. In this simulation, we use the ETSI propagation model of path loss, which can be represented as follows.

$$L = L_0 + 10\alpha \log(d) + KL_f + L_s + F, \qquad (1)$$

where d is the distance between the RFP and the PP in m, L_0 is the unit loss in dB (i.e., the loss after 1 m distance), α is the attenuation factor, K is the number of interposed floors, L_f is the attenuation per floor in dB, L_s is the shadowing factor in dB, F is the multipath fading margin in dB. We set $L_0 = 30$ dB, $\alpha = 3.5$, $K = 1$, $L_f = 15$ dB, and $L_s \sim \mathcal{U}(-10, 10)$ dB for our simulation. We assume the sensors are deployed indoors. Generally, sensors are static in industrial environment. However, movement of the machinery can trigger multipath effect. Considering multipath fading for 99% sensors, a fading margin of $F = 20$ dB is considered. However, with antenna diversity turned on, we can consider $F = 10$ dB. To setup and maintain a call with bit error rate (BER) less than 10^{-3}, a minimum SINR of 21 dB should be maintained [22], [24], [25]. During the SINR calculation, a transmission power to 23 dBm (according to DECT-ULE standard) and a background noise floor of -100 dBm are considered.

IV. RESULTS AND DISCUSSION

The novelty of the DECT-ULE system lies in its DCS mechanism. Therefore, to evaluate the performance of DECT-ULE in a dense WSN, we mainly have to evaluate the resource allocation method (i.e. DCS) of DECT. As a performance checker, we analyzed the channel selection failure, SINR of the channels (used in calls), average load per RFP and the call setup delay of the network, which are explained below.

A. *Channel selection failure*

The number of call attempts and the number channel selection failure per frame are compared in Figure 4. In case of low traffic (maximum 10 parallel calls), the number of call attempts is almost constant throughout the frames. In most of the frames, there was no channel selection failure. On the other hand, in high traffic case (maximum 100 parallel call), we see an specific pattern of call initiation. During frame 1 to 40, most of the calls have been initiated; in some cases the number of call attempts is almost 20 times higher than that of in low traffic case. Besides, during frame 40 to 100, almost no call request has been placed. The high call density pattern is again continued during frame 101 to 140 and so on, due to the periodicity of the call generation. As mentioned earlier, up to 100 new calls can be initiated per frame in high traffic case, which some times can trigger around 200 call attempts (including the re-call request of the PPs which have denied access of a channel in previous frames). All the 1000 sensors of the network can finish requesting a call within first 15-30 frames, this is the main reason of this specific pattern of call initiation. The sensors which failed to select a channel to place a call in a particular frame, can reattempt to place the call during next 17 frames[7]. As a result, we see there are still some call attempts up to the frame 40. Total 1.42% of the calls fail to select a channel in low traffic case, while 17.05% channel selection failure is observed in high traffic case. Although some sensors are failed to select a channel during first few frames, most of those are able to setup the call in next frames by reattempting for the connection. This results in a final 0.0442% lost calls in low traffic and 0.4173% in case of high traffic.[8] Therefore, it can be said that DECT standard can handle the adhoc traffic in sensor networks elegantly.

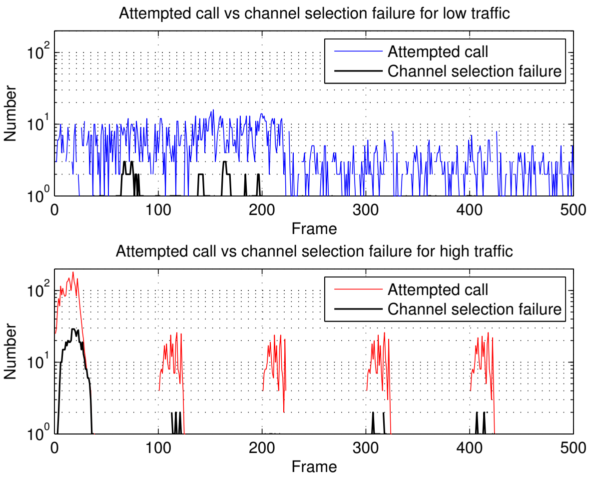

Figure 4. Attempted call vs channel selection failure for different traffic densities.

B. *SINR of the channels*

In DECT, a particular PP receives interference on a channel when the same channel has been used by other RFP-PP pairs in range. The SINR on a communication channel used by a PP-RFP pair may have different values in different frames during the call period, as the other RFP-PP pairs may or may not use the channel in question in every frames during the call period. In our simulation, we checked the SINR of every channels used for communication in every frames during the call period because a handover may take place if the SINR falls below the threshold. Again, the SINR of a channel during a frame may be different in down-link and up-link as RFPs may also have simplex channels along with duplex channels. However, we ignore such possibilities for simplicity and consider the same SINR for down-link and up-link. In our simulations, almost all the channels (99%) used for the calls are found capable to maintain the minimum required SINR (21dB marked by Green

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[7] Considering the sensor can find a signal from at least 3 RFPs and in each RFP it has at least 6 free suitable channels, the actual number of reattempt for a call can be lower for some sensors.

[8] The data of these calls can not be recovered.

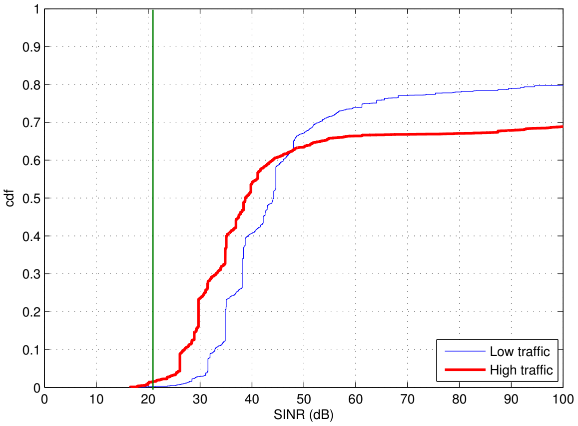

Figure 5. The cdf of SINR for different traffic densities.

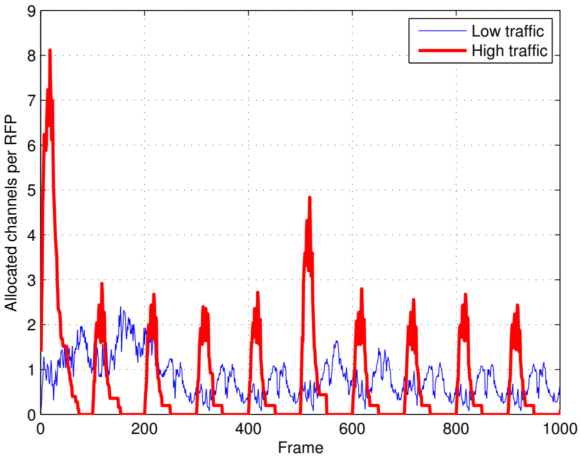

Figure 6. Average load per RFP vs frame for different traffic densities.

line) both for low and high traffic density cases, which can be visualized in Figure 5. Most of those (>90%) actually have quite high SINR that can maintain excellent call quality. As a result, the handover request due to the bad channel quality can be ignored. In the first part of Figure 5, the channels for the high traffic case have slightly lower SINR than those in low traffic case. The reason is the adhoc call initiation pattern of WSN explained in Section IV-A. As, a lot of calls have been initiated during the first few frames, the chance of getting co-channel interference is higher. Again, the high traffic case achieve higher SINR in the later part of the cdf comparison curve as there are few call attempts during frames 30-100 which decreases the probability of co-channel interference.

C. Average load per RFP

In Figure 6, the average load per RFP is shown for both low traffic and high traffic case. The average load per RFP is calculated by counting all the used channels for communication by all the RFPs in a particular frame and taking the average among all the RFPs. In case of low traffic, the average load per RFP is varying between 1-2 channels. This is far below to the maximum allowed traffic per RFP. So there is still enough room for new calls in the network. In high traffic case, the average load per RFP has some peaks due to the special call initiation pattern showed in Figure 4. Some times, the peaks reach near the maximum load capacity (i.e., 12 allocated channels per RFP). Although, the average traffic per RFP is really high for the later case, most of the channels used for the communication are able to maintain excellent quality, which is shown earlier in Figure 5. This again justify the robustness of DECT in high traffic WSNs.

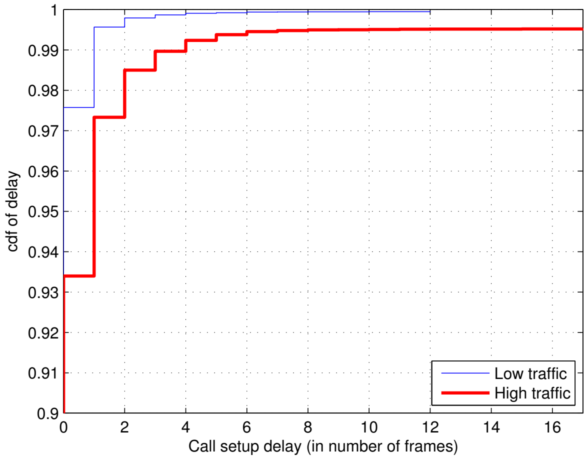

Figure 7. The cdf of call setup delay for different traffic densities.

D. Call setup delay

Another important issue in any communication network is the latency, which has been overlooked in most of the WSN applications. However, we have to consider this issue for many recently envisioned WSN applications where real-time communication should be guaranteed. In Figure 7, we analyzed the call setup delay for both high traffic and low traffic scenarios. In both cases, we observe that more than 90% calls have been established without any delay, i.e., in the same frame where the call setup request has been sent.[9] Only a few calls (less than 1% in low traffic case and less than 2% in high traffic case) require more than 2 re-call attempts to find a suitable channel for call setup. This really fits with the requirements of previously mentioned applications.

V. CONCLUSIONS AND FUTURE WORKS

Dynamic channel selection is the heart of the DECT system which enables the portables to re-use the radio resources in a flexible and distributed way. In this paper, we have evaluated the potential of DECT-ULE for robust communications in WSNs by analyzing the DCS algorithm. The simulations have been carried in a dense network condition; different traffic scenarios (low and high) have been tested. Though, DECT was

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[9] In practical systems PPs generally scans two future frames after selecting a channel for call setup. In our simulation we ignore this part.

intended to use in enterprise wireless voice communications, we found that DECT-ULE can beautifully handle dense WSN by providing *excellent channel quality* to place a call with *minimum delay*. Only a few call attempts have been denied to grant a channel on first attempt in our simulation, which have been taken care of by placing the call on some other suitable channel in next frames.

Nevertheless, the DECT-ULE standard is able to support many requirements of industrial WSN applications, we also identify some limitations of DECT. So, there are still rooms for improvement to make DECT more suitable for WSNs. The installation cost of DECT-WSN might be high as fixed infrastructures are essential for DECT base stations. Future works include the cooperative channel selection algorithm, increased communication reliability and recovery of lost data, transmission power control, etc. It will also be interesting to compare the performance of DECT-ULE with existing WSN standards such as WirelessHART.

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