# An Efficient Channel-aware Aloha-like OFDMA-based Wireless Communication Protocol for IoT Communications in Wireless Sensor Networks

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**Abstract**

Wireless sensor networks consisting of several sensors deployed in a given area, under an internet of things (IoT) paradigm, are considered. Sensor nodes may or may not be close enough to communicate with each other in order to perform collaborative transmissions. A communication protocol is proposed in order to allow the sensors to operate autonomously by transmitting their measured data to a central processing system, where it is processed and analyzed. The presented communication protocol is based on random access. It allows each sensor to independently access the channel whenever it has data to transmit. It is based on orthogonal frequency division multiple access (OFDMA), where each sensor accesses a time-frequency slot in a probabilistic manner to avoid collisions. A controlling entity, e.g., a central base station (BS) covering a certain sensor deployment area receives the sensor transmissions. The BS provides synchronization information to the sensors by periodically transmitting a pilot signal over the available OFDMA subcarriers. Sensors use this signal for channel quality estimation, which can guide them in their transmission slot selection. This approach is simple, flexible, and efficient in terms of energy consumption, transmission data rates, and collision probability. A typical application example consists of an autonomous sensor network deployed for monitoring air quality and environmental pollution.

## 1. Introduction

The Internet of Things (IoT) is expected to be a key enabler for smart cities, where sensor and actuator devices will be ubiquitous and will monitor every aspect of our lives (Ejaz et al., 2017). With the billions of devices expected to be deployed under the IoT paradigm, next generation cellular networks are expected to face enormous challenges (Chen, 2012). In fact, they need to be able to support this large number of devices through the use of machine-to-machine (M2M) communications. The quality of service (QoS) requirements of IoT devices are expected to be varying and different, depending on the purpose for which each device was designed. Thus, these devices will affect the network in different ways since they will have different behaviors. For certain devices, the network will need to be accessed in a frequent and periodic manner for the sake of transmitting small amounts of measurement data. This would be the case in advanced metering infrastructure (AMI) where smart meters deployed in a smart grid setup would be sending their data (Yaacoub & Kadri, 2015). In other scenarios, it could be possible for devices to temporarily store their measured data and then transmit the stored data in bulk later on. A typical example would be the case of sensor networks deployed for monitoring the environment (Lloret et al., 2015). Indeed, the IoT will significantly consist of wireless sensor networks (WSNs) comprising a number of sensor nodes (SNs) that capture certain information and then transmit it wirelessly over the network (Mainetti et al., 2011). WSNs have a broad spectrum of applications. They can be used in intelligent transportation systems for road safety purposes, in military applications for border control and surveillance, and in environmental applications for the sake of air pollution monitoring, detection of water pollution, smart agriculture, etc. (Vieira et al., 2003).

An SN is, in most cases, an autonomous device that comprises: a sensing unit to measure the required data, a processing unit to process and (temporarily) store the measured information, a communication unit to transmit the data over the network, and a power unit to provide power for the device. Generally, the most important limiting factor for the operation of an SN is power consumption, since it is expected to operate for extended periods in areas where power infrastructure could be absent. Consequently, SNs should have the capability to perform their intended tasks with very low power consumption. Certain SNs can be powered by batteries that benefit from energy harvesting from the environment and thus, for example, can use solar power to replenish their energy, which allows them to operate autonomously for a longer time. Energy saving can also occur via the wireless communication unit. In fact, short range ad-hoc communication between SNs in a WSN via multihop communications can prove to be more energy efficient than a single hop long distance transmission to a base station (BS) or access point (AP) (Vieira et al., 2003).

In this Chapter, a wireless communication protocol for WSNs is presented and analyzed. It is an extension of the protocol presented in (Yaacoub et al., 2011) in order to apply it in various WSN scenarios. The presented protocol deals with the communication between SNs and APs or BSs. It is however applicable to scenarios where multihop communications take place in WSNs. In such scenarios, SNs communicate with each other over multihop links using a pre-defined communication protocol, and the SN at the last hop communicates with the BS by relaying the aggregated multihop data using the approach discussed in this Chapter. The presented protocol enables SNs to communicate efficiently with an AP by operating autonomously in different parts of the cell area covered by the BS or AP. It is a channel aware extension of slotted reservation

Aloha to orthogonal frequency division multiple access (OFDMA) systems.

The chapter is organized as follows. Section 2 presents the relevant background/literature review. The proposed approach is presented in Section 3. Simulation results are presented and analyzed in Section 4. Finally, in Section 5, conclusions are drawn and future research challenges are outlined.

**2. Literature Review**

In IoT systems, with excessively large deployments of SNs, centralized resource allocation becomes extremely challenging due to high computational complexity and increased overhead. Thus, a distributed resource allocation approach might be more convenient. Game theory is generally a good tool in such scenarios. However, conventional game models still suffer slow convergence and excessive overhead in in such large-scale systems (Semasinghe et al., 2017). A modification of Bluetooth presenting a low power alternative called Bluetooth Low Energy (BLE), results in high collision rates and wasted energy when applied in an IoT scenario (Harris et al., 2016). To alleviate this problem, opportunistic listening was proposed in (Harris et al., 2016). To provide sufficient spectrum for the large expected traffic demand in IoT/Cyber-Physical systems, a shared spectrum access model in Radar bands is proposed in (Khan et al., 2017).

Thus, distributed scheduling methods along with dynamic spectrum random access seem to be recognized as the most efficient methods for IoT, with several challenges still to be overcome. This chapter proposes an enhancement of the Aloha method to address these challenges.

In fact, Aloha can be considered as one of the first random access algorithms (Roberts, 1973). In general, it is investigated under the assumption that there is a single channel assumption, and users contend to transmit over that channel. An enhancement was made with slotted Aloha, where users cannot transmit at any time, but rather can send their packets during time slots of fixed length. Collision would occur whenever more than one user attempt to transmit simultaneously in the same time slot (Shen & Li, 2002). Reservation Aloha is another variant that was proposed in order to reduce collisions (Roberts, 1973). In this scheme, reservation slots of short duration precede the actual transmission slots of fixed length (similarly to slotted Aloha). Transmission requests are sent in the small reservation slots during a reservation phase, using the slotted Aloha random access technique, in order to reserve the actual transmission slots. This allows collisions to occur in the reservation phase before actual transmission, thus preventing more serious collisions during the transmission phase.

Reservation Aloha is used in several applications, including satellite networks (Lepaja & Benji, 2001), wireless local area networks (WLANs) (Tasaka et al., 1995), and vehicle-to-vehicle communication (Alsbou et al., 2010). The implementation of classical Aloha (without reservation) was even studied for communication in underwater acoustic sensor networks (Xiao et al., 2009). With the adoption of OFDMA as the accessing scheme in state-of-the-art cellular systems like the long term evolution (LTE) and LTE-Advanced (LTE-A), in addition to WiMAX, extensions of Aloha and its variants to OFDMA-based networks were investigated in the literature (Shen & Li, 2002; Choi et al., 2006; Han et al., 2006; Ganesan & Li, 2007; Wang et al., 2009; Yumei & Su, 2009). OFDMA consists of a set of orthogonal subcarriers. In general, a fixed number of consecutive subcarriers are grouped to form a subchannel, and thus they can be allocated together to a user for transmission (Shen & Li, 2002; Lunttila et al., 2007).

In (Shen & Li, 2002), slotted Aloha over OFDM was studied. In (Choi et al., 2006), the authors presented a backoff scheme for multichannel slotted Aloha. In the approach of (Choi et al., 2006) backoff is performed on different subchannels instead of performing backoff on a different time slot on a single subchannel. In (Han et al., 2006), a class of multichannel MAC schemes based on Aloha contention resolution and on the RTS/CTS (Ready-To-Send/Clear-To-Send) dialogue is investigated. In the approach of (Han et al., 2006), a single subchannel called the control subchannel is used to transmit the RTS/CTS dialogues, whereas the other subchannels are dedicated for data transmissions. The RTS packets contend on the right to use one of the data subchannels. The winner in a contention can then use one of the data subchannels for transmission without facing the risk of collisions. This method was shown in (Han et al., 2006) to reduce collisions for a fixed total bandwidth scenario. However, the sum-rate of the multichannel MAC schemes was shown to be less than that of the corresponding single channel MAC scheme that sends the RTS/CTS and data packets on a single shared channel. Channel sensing was used in (Kwon et al., 2009) to deal with this problem. Thus, in (Kwon et al., 2009), carrier sense multiple access with collision avoidance (CSMA/CA) over OFDMA is proposed, and a backoff mechanism is investigated without resorting to slotted reservation.

In (Wang et al., 2009), an OFDMA-based reservation Aloha scheme is proposed. Users compete for subcarriers in the contention period, and the winner transmits over the reserved subcarrier until the next contention period. Furthermore, channel state information (CSI) is assumed to be known by the users when they access the channel. Capture effects are not investigated in (Wang et al., 2009). With capture effects, even if some collisions occur during the contention period, the BS could still succeed in detecting one of the contending users and allow this user to transmit over the corresponding slot. In (Zhang et al., 2006), CSI awareness is not assumed, but collisions are resolved through the use of the capture effect: users with better channels succeed in accessing the channel through this effect and thus this exploitation of multiuser diversity allows reaching enhancements in reservation Aloha. In (Ganesan & Li, 2007), a scheme for reservation Aloha with CSI is proposed, where capture effect is used for collision resolution and a user reserves the OFDMA subchannel for the whole transmission time of a frame. In (Yumei & Su, 2009), slotted Aloha is investigated and a Markov model of the wireless channel is adopted: In this model, slotted Aloha is implemented by users to transmit on a subchannel in “good” state, whereas no transmission occurs on a subchannel if it is in the “bad” state.

In this Chapter, reservation Aloha over OFDMA is investigated. The proposed approach uses a frequency-time grid for reservations, in contrast to classical reservation Aloha where the reservation of time slots occurs over the whole bandwidth (Roberts, 1973; Alsbou et al., 2010), and as opposed to the OFDMA extensions of reservation Aloha (Han et al., 2006; Ganesan & Li, 2007; Wang et al., 2009), where an OFDMA subchannel can be reserved for the whole transmission period of the frame. A WSN scenario is considered, where a group of SNs are assumed to communicate with a single receiver, such as an AP or BS. With the proposed approach, the transmission frame is subdivided into several time-frequency slots. SNs contend for a particular transmission slot over a certain subchannel such that, in a given Aloha frame, several SNs could be transmitting on the same subchannel but at different time slots, and several

SNs could be transmitting at the same time but over different subchannels. The presented scheme is compared to other schemes and is shown to lead to significant improvements.

**3. Channel-Aware OFDMA-Based Aloha Protocol for Wireless Sensor Networks**

In this section, the proposed protocol is presented. The proposed approach uses a frequency-time grid for reservations, in contrast to classical reservation Aloha where the reservation of time slots occurs over the whole bandwidth (Roberts, 1973), and as opposed to subchannel reservation (Ganesan & Li, 2007; Wang et al., 2009), where an OFDMA subchannel can be reserved for the whole transmission period of the frame.

In fact, reservation in slotted reservation Aloha is performed over transmission slots in the time domain in an approach similar to time division multiple access (TDMA). All the bandwidth is used for transmission, e.g., (Roberts, 1973; Thomopoulos, 1988). In this Chapter, an extension of slotted reservation Aloha to OFDMA is considered in order to perform a fair comparison with the presented approach. It will be referred to as the TDMA approach and it is shown in Fig. 1. Thus, if an SN reserves a certain time slot, it will transmit over all the subcarriers for the duration of that slot. The extension of Fig. 1, in addition to using OFDMA in the reserved transmission slots, makes use of channel knowledge in the reservation phase. Consequently, similarly to the proposed approach, the OFDMA reservation Aloha scheme shown in Fig. 1 contains a channel estimation phase that permits to SNs to estimate the data rate that they can achieve over a reserved slot.

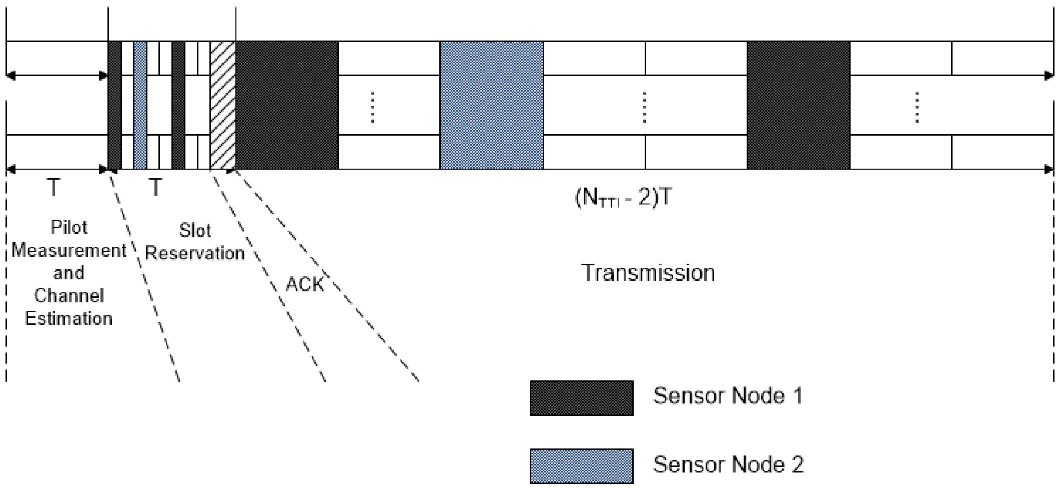


Fig.1. TDMA approach.

With the wide adoption of OFDMA in wireless communications systems, several random access schemes based on OFDMA were presented in the literature (Wang et al., 2009; Yumei & Su, 2009). A common aspect for all these schemes is that reservations are made over subchannels. Then, a single user is allowed to transmit over a reserved subchannel. Transmission lasts until the next frame where a new reservation is performed. In this Chapter, these schemes are extended in order to take into account pilot measurement and channel state information (CSI) estimation so that SNs can benefit from channel knowledge while making their reservations during the reservation phase. This subchannel reservation scheme, shown in Fig. 2, will be referred to as the FDMA approach in this Chapter.

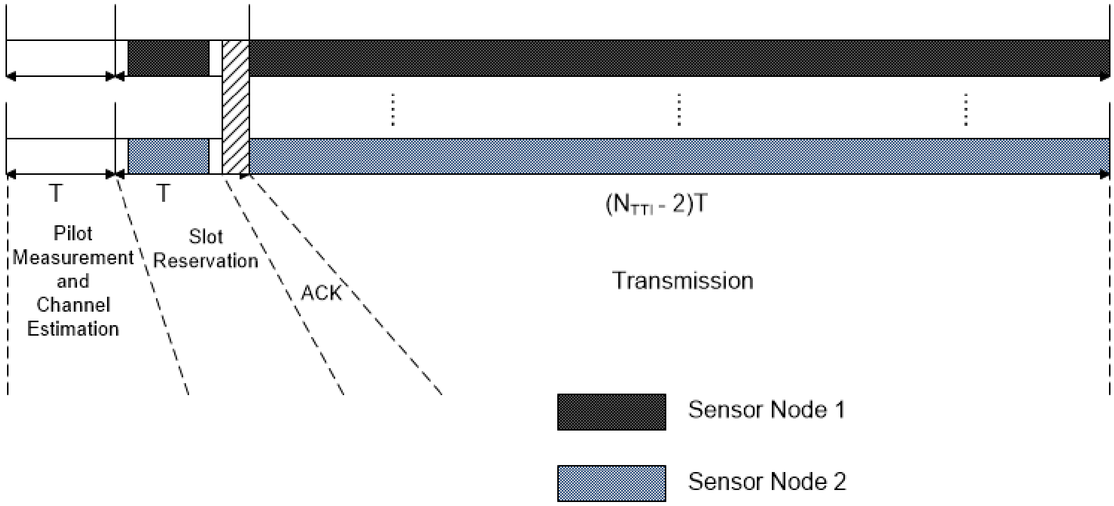


Fig.2. FDMA approach.

### *3.1 Details of the Proposed Approach*

The proposed method allows performing distributed resource allocation for SNs over OFDMA. In this approach, SNs can compete over transmission slots, or transmission time intervals (TTIs), over all the available subchannels. It is illustrated in Fig. 3. Each frame of duration $N_{TTI}$ is subdivided into three phases: a pilot transmission and channel estimation phase of duration 1 TTI, a reservation phase of duration 1 TTI, and a transmission phase of duration $N_{TTI} - 2$, with each TTI having a duration $T$. The proposed method can be described as follows:

- Step 1: A pilot signal is transmitted by the BS over the available subchannels. Each SN in the cell covered by that BS measures the received pilot power and performs CSI estimation over each subchannel.

- Step 2: Each SN performs a sorting operation for its subchannels in decreasing order of CSI.

- Step 3: In the reservation phase, there are $N_{TTI} - 2$ small reservation slots over each subchannel. After sorting the subchannels in decreasing order of CSI, each SN goes sequentially through its subchannels. It makes a decision to transmit over a subchannel $i$ with a probability $p_T(k, i) = f(Rank(k, i))$, where $Rank(k, i)$ is the position of i in the sorted list of subchannels and $f(Rank(k, i))$ is a function of $Rank(k, i)$. This equation indicates that the transmission probability is selected as function of the rank of $i$ in the sorted list. Thus, an SN is more likely to transmit over subcarriers with good channel conditions (having a high CSI). In case the SN decides to transmit, it randomly selects one of the $N_{TTI} - 2$ small reservation slots over that subchannel and transmits a reservation signal in that slot.

- Step 4: The SN estimates its achieved data rate on the selected slot. If it is not sufficient to reach its target rate mandated by its QoS requirements, it moves to the next subchannel and repeats the same operation. In case it goes over all subchannels without achieving the target rate, the SN returns to the first subchannel and repeats the process. This iterative approach continues until the SN achieves its target rate or until a pre-defined maximum number of slots are reserved.

- Step 5: Once the reservation phase is complete, the BS transmits an ACK message containing $N_{sub}(N_{TTI} - 2)$ bits, with $N_{sub}$ representing the number of subchannels. These bits correspond to the reservation slots over all the subchannels. If a reservation was successfully made on a given TTI over a certain subchannel, the corresponding bit is set to 1. However, in case a collision has occurred during the reservation phase, or even when no reservation was made, the bit is set to 0. Consequently, an SN that attempted to reserve a slot and found a 1 in the corresponding bit in the ACK message knows that the slot was successfully reserved. In case it encounters a 0, it knows that a collision has occurred and thus refrains from transmitting on that slot.

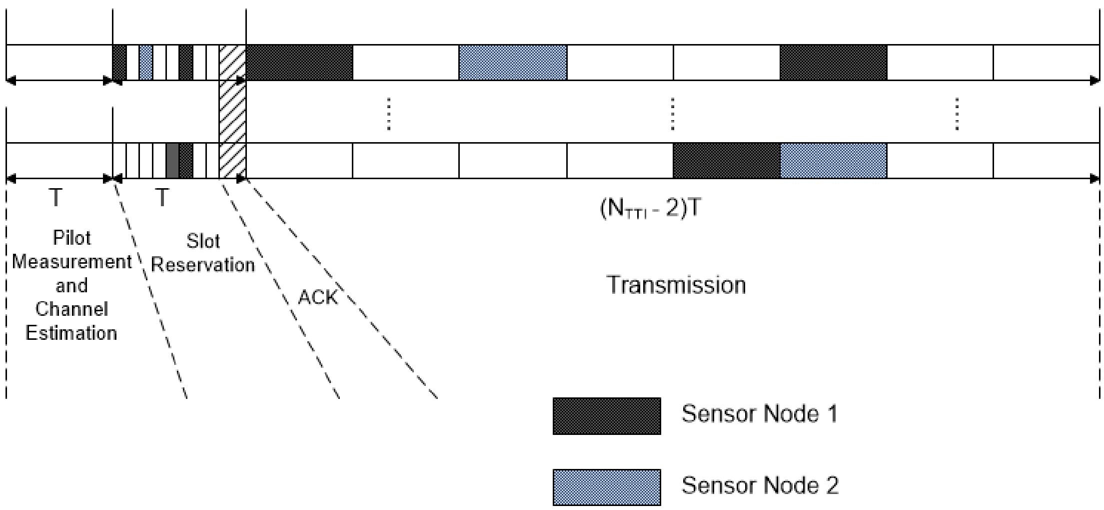


Fig.3. Proposed OFDMA-based Aloha-like approach.

This proposed approach has the benefit of allowing collisions to occur only in the reservation phase, but not in the transmission phase. Thus, it avoids unnecessary transmissions and wasted power, which is a scarce resource in WSNs. Furthermore, collision detection is done at the BS. Consequently, there is no need for SNs to perform channel sensing in order to detect the transmissions of other SNs, as in the 802.11 standard for example. This allows avoiding the hidden terminal problem and leads to more efficient collision detection. Hence, once a collision is detected at a given slot, no transmission occurs in that slot. It should be noted that the pilot signal transmitted by the BS at the beginning of each frame has an important role in the proposed approach: It allows the SNs to keep their synchronization with the BS, while also being used by the SNs for CSI estimation.

### *3.2 Data Rate Calculations*

A single cell uplink orthogonal frequency division multiple access (OFDMA) system is considered. It is assumed that there are $K$ sensor nodes (SNs) and $N$ subcarriers to be allocated. For each SN $k$ and subcarrier $i$, the transmit power, channel gain, and total noise power are respectively denoted by $P_{k,i}$, $H_{k,i}$, and $\sigma^2_{k,i}$. The signal-to-noise ratio (SNR) is given by:

$$\gamma_{k,i} = \frac{P_{k,i} H_{k,i}}{\sigma^2_{k,i}} \quad k = 1,\ldots,K; \quad i = 1,\ldots,N; \tag{1}$$

Each SN $k$ operates under a peak power constraint given by:

$$\sum_{i=1}^{N} P_{k,i} \le P_{k,\max} \qquad k = 1,\ldots,K; \tag{2}$$

This constraint indicates that the power spent by the SN over all its allocated subcarriers cannot exceed its maximum transmission power $P_{k,\max}$.

The total data rate achieved by SN $k$ is given by:

$$R_k = \sum_{i=1}^{N} R^d_{k,i}(\gamma_{k,i}) \tag{3}$$

where $R^d_{k,i}$ is the discrete rate of SN $k$ over subcarrier $i$. Conversely to continuous rates, which can take any non-negative real value according to the Shannon capacity formula $\log_2(1 + \gamma_{k,i})$, discrete rates represent the quantized bit rates achievable in a practical system as follows:

$$R^d_{k,i}(\gamma_{k,i}) = \left\{ \begin{array}{ll} r_0, & \eta_0 \le \gamma_{k,i} < \eta_1 \\ r_1, & \eta_1 \le \gamma_{k,i} < \eta_2 \\ r_2, & \eta_2 \le \gamma_{k,i} < \eta_3 \\ \vdots & \\ r_{L-1}, & \eta_{L-1} \le \gamma_{k,i} < \eta_L \end{array} \right\} \tag{4}$$

In (4), $\eta_l$ corresponds to the target SNR required to achieve the rate $r_l$ with a predefined bit error rate (BER). It should be noted that in the limit, $r_0 = 0$, $\eta_0 = 0$, and $\eta_L = \infty$. Thus, the sum-rate of the system can be expressed as:

$$R_{tot} = \sum_{k=1}^{K} \sum_{i=1}^{N} R_{k,i}^{d} (\gamma_{k,i}) \qquad (5)$$

The channel gain of SN $k$ over subcarrier $i$ is given by:

$$H_{k,i,dB} = (-\kappa - \lambda \log_{10} d_k) - \xi_{k,i} + 10 \log_{10} F_{k,i} \qquad (6)$$

In (6), the first factor captures propagation loss, with $\kappa$ the pathloss constant, $d_k$ the distance in km from SN $k$ to the BS, and $\lambda$ the path loss exponent. The second factor, $\xi_{k,i}$, represents log-normal shadowing, assumed to have a zero-mean and a standard deviation $\sigma_\xi$, and the last factor, $F_{k,i}$, corresponds to Rayleigh fading with a Rayleigh parameter $a$ such that $E[a^2] = 1$, with $E[]$ being the expectation operator.

### *3.3 Reservation Policy to Achieve the Target Data Rates*

A single cell scenario is considered, with SNs competing for resources to communicate with a BS by using the presented communication protocol. SNs are assumed to perform continuous monitoring of an environmental parameter. For example, a measurement is taken every few seconds or minutes. The measured data can be transmitted immediately or several measurements can be aggregated before transmission, which leads to different target transmission rates needed, depending on the scenario. Thus, SNs always have data to transmit, and each SN has to meet a target average data rate $R_T$. If an SN fails to achieve this data rate after a certain number of frames $N_{frames}$, the SN can be considered to be in outage. SNs regulate their transmissions in order to achieve $R_T$ after $N_{frames}$. The procedure they follow is described next. The number of bits that should be transmitted in order to achieve $R_T$ after $N_{frames}$ is given by:

$$N_{b,T} = R_T \cdot N_{frames} \cdot N_{TTI} \cdot T \quad (7)$$

Denoting by $n_F$ the number of the current frame in a window of length $N_{frames}$, and by $N_{b,nf}$ the number of bits transmitted in frame $n_f$, the number of previously transmitted bits is expressed as:

$$N^{(p)}_{b,n_F} = \sum_{n_f=1}^{n_F-1} N_{b,n_f} \quad (8)$$

Consequently, an SN makes enough reservations in frame $n_f$ in order to transmit $N_{b,nf}$ bits with:

$$N_{b,n_F} = \frac{N_{b,T} - N^{(p)}_{b,n_F}}{N_{frames} - (n_F - 1)} \quad (9)$$

Hence, an SN attempts to subdivide the remaining $(N_{b,T} - N^{(p)}{}_{b,nF})$ bits equally over the remaining $[N_{frames} - (n_F - 1)]$ frames.

### *3.4 Setting the Transmission Probabilities in the Proposed Approach*

This section is dedicated to describing the selection of the values of the transmit probabilities $p_T(k, i) = f(Rank(k, i))$. The function $f(Rank(k, i))$ is chosen as a decreasing function with respect to $Rank(k, i)$, whereas $p_T(k, i)$ has to take values in the interval $[0\ 1]$ since it is a probability measure. Consequently, SN $k$ has a higher transmission probability on subchannels having good channel conditions. Thus, a better channel state information (CSI) for SN $k$ on a given subchannel means this subchannel has higher chances of being selected for transmission.

A simple approach would be to select:

$$p_T(k, i) = p_T \quad (10)$$

i.e., use constant probabilities for all SNs and subchannels. This would favor subchannels having better channel conditions through by the sorting process only, not through the transmission probabilities. On the other hand, we can set:

$$f(Rank(k, i)) = p_{T0}/ Rank(k, i) \quad (11)$$

where $p_{T0}$ is a constant. In (11), a simple straightforward approach is presented in order to make the transmission probability of SN $k$ over subchannel $i$ vary with its CSI level: a high CSI leads to a lower $Rank(k, i)$, and thus to a higher transmission probability. The constant $p_{T0}$ should ideally be set to a value close to 1, e.g. 0.9, in order to increase the transmission probability on subchannels that are positioned higher in the sorted list. Thus, the transmission probability on the first subchannel in the list will be 0.9; whereas the transmission probabilities on the second and third subchannels will be 0.9/2 = 0.45 and 0.9/3 = 0.3, respectively, and so on.

A more aggressive reservation strategy could use, for example, a function of the form:

$$f(Rank(k, i)) = p_{T0}/ [c_1 log_b(c_2 Rank(k, i)+ c_3)] \quad (12)$$

With $b$ the base of the logarithm and $c_1$, $c_2$, and $c_3$ are constants selected such that the value of the transmission probabilities remains in the interval $[0\ 1]$. The selection of a logarithmic variation for the probabilities allows a slow decrease with the rank of the subchannel in the sorted list; consequently, even when the CSI decreases, the transmission probabilities would generally be higher than the case represented by Eq. (11).

On the other hand, a more restrictive approach can use functions of the form:

$$f(Rank(k, i)) = p_{T0}/ [c_1\ exp(c_2 Rank(k, i)+ c_3)] \quad (13)$$

The selection of an exponential variation for the probabilities in Eq. (13) allows a fast decrease with the rank of the subchannel in the sorted list; therefore, when the CSI decreases, the transmission probabilities would generally be lower than the case of Eq. (11). Consequently, each SN will concentrate its transmissions on its subchannels having the best channel conditions.

### *3.5 Possible Implementation in a practical LTE system*

This section describes a possible implementation of the proposed IoT communication approach in a practical cellular system, e.g. LTE/LTE-A. In fact, with 3GPP LTE, OFDMA is used in the downlink (DL) direction. In the uplink (UL) direction, a modified form of OFDMA called single carrier frequency division multiple access (SCFDMA) is used. The LTE spectrum is subdivided into resource blocks (RB) where each RB consists of 12 adjacent subcarriers. The shortest allocation time of a single RB is 1 ms, known as the duration of one transmission time interval (TTI), or the duration of two 0.5 ms slots in LTE (3GPP TS 36.211; 3GPP TS 36.213). With the expected large numbers of SN devices in a typical IoT deployment, congestion would be natural to occur whenever the SNs use the cellular network for their communications. However, the amount of data to be sent by each sensor is generally limited; which contrasts with the much larger data rates that can be supported by the smallest LTE allocation unit. This problem is solved by the proposed method that subdivides the LTE RBs into their corresponding smaller subchannels of pre-defined size. Then, it allows the devices to compete dynamically by contending over the subchannels of the RBs that are not scheduled by the BS at a given instant. Thus, the proposed approach is channel-aware, energy efficient, OFDMA based, and can use subsets of the LTE RBs for transmission. Consequently, it allows the spectrum to be used efficiently without interfering with the traffic dedicated to LTE mobile users.

In fact, the proposed approach could make use of a device acting as access point AP/controller/coordinator, covering a geographical area and deployed in a strategic location, preferably co-located with a cellular BS covering the same area. It is referred to as AP in the sequel. The AP communicates with IoT devices that could be either SNs communicating directly with the AP, or aggregators collecting information from SNs and relaying it to the AP. The AP informs the devices in the network of the free wireless channels available for transmission, and handles communication with these devices. The AP receives the data from the devices and routes it over a backbone network to the servers of the utility provider. The devices should be enabled with OFDMA wireless transmission capability in order to communicate with the AP according to the proposed method. The details of the practical implementation of the proposed approach in an LTE system are summarized in Fig. 4, and can be described as follows:

- The AP uses the cellular bandwidth that is subdivided into subchannels of fixed size.
- The AP communicates with the radio resource management (RRM) module of the cellular BS in a periodic fashion, in order to get a list of the channels that will be free for an estimated time period, specified by the RRM module. Typically, this time period could be from the order of tens of milliseconds. It should be relatively small so that the proposed method does not impact the RRM process of cellular users, since the free channels can be used later by the BS. Nevertheless, this does not prevent the time period from being longer whenever the BS channel assignments are less frequent in case the LTE cellular network dynamics are varying slowly.
- The AP sends periodic pilot signals to the SNs over the available cellular spectrum as indicated by the BS. The signal is non-zero only over the free subchannels, and it is zero over the ones occupied by the cellular system. Thus, devices know which subchannels are available for transmission during the next frame duration. An example is shown in Fig. 5. Furthermore, this periodic pilot transmission process allows the devices to periodically adjust their synchronization with the AP. It should be noted that SNs are aware of the full spectrum range that can be used, e.g. the spectrum dedicated for LTE cellular transmission, and that they are allowed to transmit

on the free spectrum blocks. Although they expect the AP to transmit periodically a pilot signal over the whole LTE spectrum, they know that a particular channel is not available if the pilot signal level received over that channel is zero. If the pilot level higher, they implement the proposed channel-aware approach by ranking the channel according to its received signal strength as described in the previous sections. In the example of Fig. 5, for illustration purposes, one LTE channel is subdivided into four subchannels that can be used with the proposed method.

- SNs measure their channel quality on the subchannels and make channel-aware decisions during a reservation slot, by contending over the subchannels needed for their data transmission. The intelligent channel aware decision making process can be imbedded in the devices processing units, where it makes use of probabilistic decision making: The probability of a device contending for a subchannel increases with the quality of the wireless link between the SN and AP over that subchannel, as described previously.
- The AP informs the devices of the successful reservations
- In the transmission phase, the transmissions take place only on the time/frequency slots where successful reservations were made. Hence, significant energy savings can be achieved since collisions might occur only in the reservation phase, but not in the transmission phase.

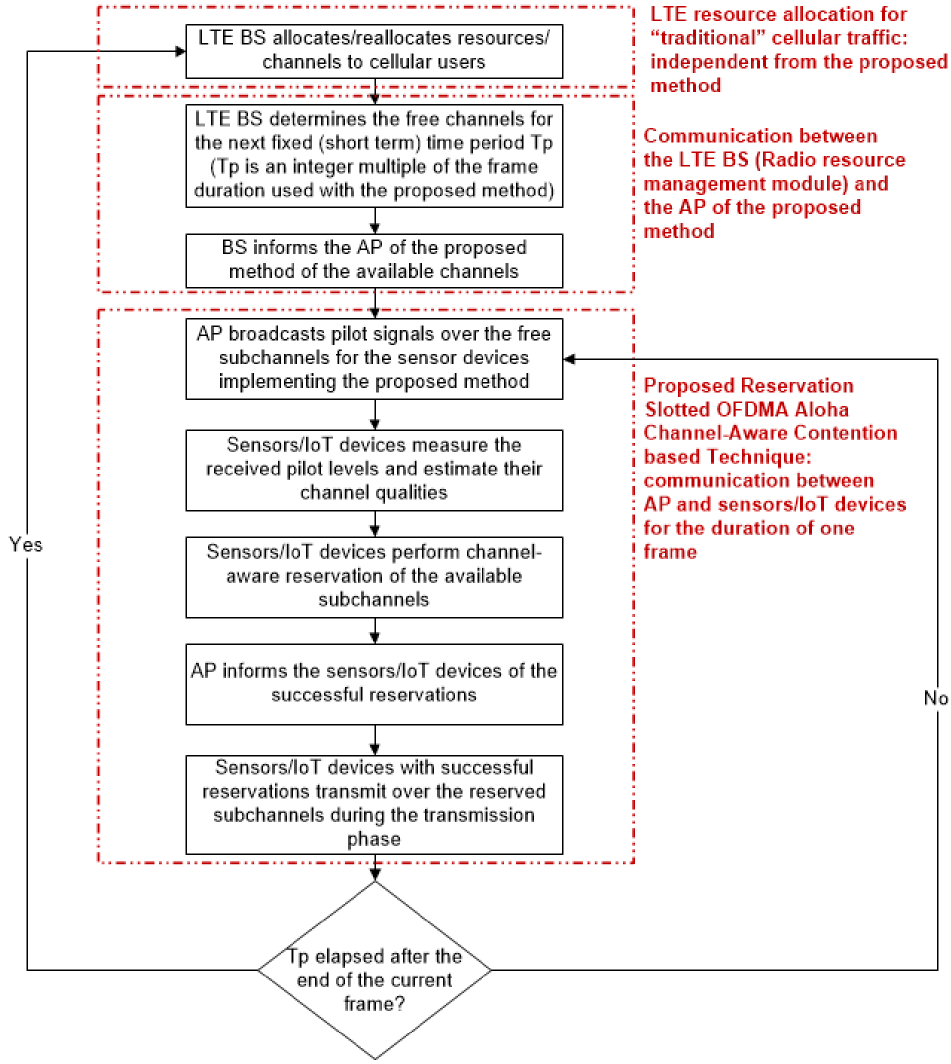


Figure 4. Flowchart describing the operation of the proposed method with collaboration from LTE BSs.

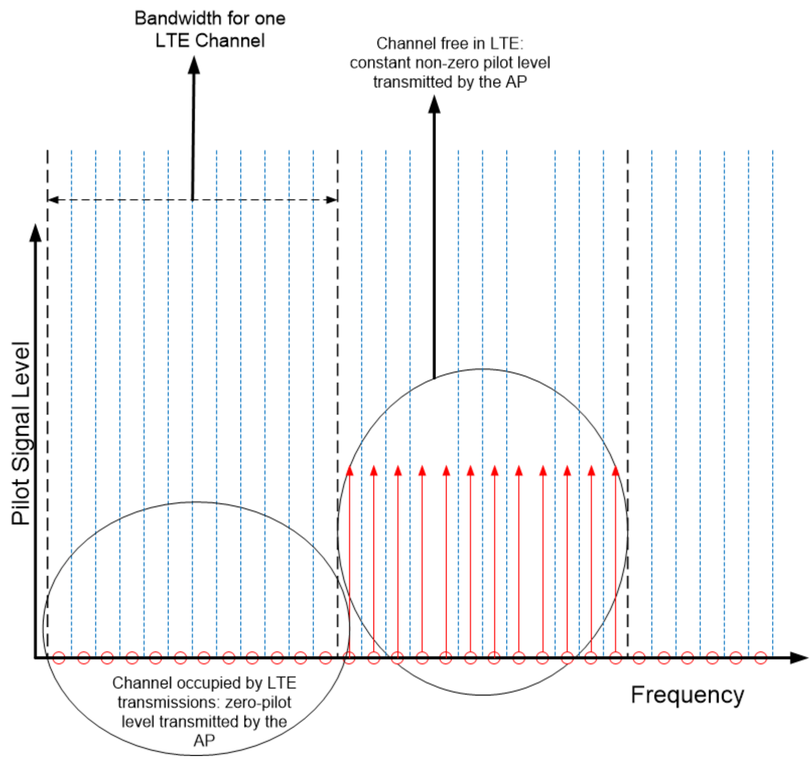


Figure 5. Pilot signal transmission on the available (free) LTE channels.

### *3.6 Simulation Parameters*

The proposed approach was presented in the previous sections. The following section presents detailed simulation results along with the relevant performance analysis and comparison to other methods. Whenever possible, the values for the parameters used in the simulation are set in compliance with the LTE standard. Nevertheless, it is worth mentioning that the proposed method is an Aloha based approach and can be implemented with any system using OFDMA. The selection of parameters in-line with the LTE/LTE-A standards is to complement the discussion of the previous section, where a possible implementation of the proposed method in an LTE/LTE-A system, in order to support the anticipated IoT/Cyber-Physical systems traffic, is presented.

Thus, in this section, the simulation parameters used throughout the Chapter are described. These parameters are common to all the investigated scenarios. Parameters that are specific to a particular scenario are described in the relevant section.

Each frame is assumed to comprise $N_{TTI} = 10$ transmission time intervals (TTIs), i.e., eight of these TTIs are dedicated for transmission. Each SN would attempt to achieve its target rate as described previously, and it is considered be in outage if it does not succeed to reach the target rate after $N_{frames} = 100$ frames. The duration of a TTI is set to 1 msec, sufficient to transmit 12 symbols over each subcarrier (3GPP TS 36.211). Results are averaged over 50 iterations, each corresponding to 100 frames. The bandwidth considered is set to $B = 5$ MHz. The maximum SN transmit power is considered to be 125 mW. All SNs are assumed to transmit at the maximum power, and the power is subdivided equally among all subcarriers allocated to the SN.

In Eq. (6), $\kappa$ is set to 128.1 dB, and $\lambda$ is set to a value of 3.76. For log-normal shadowing, $\sigma_{\xi} = 8$ dB is used. The SNR thresholds of the various modulation and coding schemes are shown in Table 1 (Yaacoub et al., 2011).

Table 1. Discrete rates and SNR thresholds with 14 modulation and coding schemes

| MCS | $r_l$ (bits) | $\eta_l$ (dB) |
|---|---|---|
| No Transmission | 0 | $-\infty$ |
| QPSK, R = 1/8 | 0.25 | -5.5 |
| QPSK, R = 1/5 | 0.4 | -3.5 |
| QPSK, R = 1/4 | 0.5 | -2.2 |
| QPSK, R = 1/3 | 0.6667 | -1.0 |
| QPSK, R = 1/2 | 1.0 | 1.3 |
| QPSK, R = 2/3 | 1.333 | 3.4 |
| QPSK, R = 4/5 | 1.6 | 5.2 |
| 16-QAM, R = 1/2 | 2.0 | 7.0 |

| | | |
|---|---|---|
| 16-QAM, R = 2/3 | 2.667 | 10.5 |
| 16-QAM, R = 4/5 | 3.2 | 11.5 |
| 64-QAM, R = 2/3 | 4.0 | 14.0 |
| 64-QAM, R = 3/4 | 4.5 | 16.0 |
| 64-QAM, R = 4/5 | 4.8 | 17.0 |
| 64-QAM, R = 1 (uncoded) | 6.0 | 26.8 |

### 4. Simulation and Results – Scenario of a Sensor Network for Air Pollution Monitoring

The communication protocol presented in this Chapter can be implemented in various WSN scenarios. In this section, an implementation scenario related to WSNs for air pollution monitoring is studied as an illustrative example. The same approach can be applied for other scenarios such as: water pollution monitoring, home automation (a multitude of sensors sending measurement data to an AP installed inside a home), etc.

In fact, monitoring of environmental parameters is an important application of WSNs, especially with the technology advancements leading to the production of small, lightweight, low power sensors that can monitor environmental parameters with increasing accuracy. These advancements facilitate the deployment of WSNs for the continuous monitoring of air quality. The concentration of pollutants in the atmosphere can be measured and reported by the SNs, and the measurements can be shared with the concerned public through websites, mobile applications, etc. Furthermore, the measurements sent by the SNs can be stored on a server for advanced processing. This can be performed by expert environmental scientists who analyze and assess pollution information and can accordingly send recommendations to the relevant authorities in order to take appropriate action.

### *4.1 Description of the Sensor Network Setup for Detecting Air Pollution*

In this section, a high level overview of the system architecture is presented. Furthermore, the role of the SNs is described. The investigated system is shown in Fig. 6, where the architecture consists of three tiers:

1) The sensor nodes (SNs): they include the sensors that measure the level of pollutants in the atmosphere. Typical monitored pollutants include: carbon monoxide (CO), nitrogen oxides (NOx), Ozone, and Particulate Matter (PM). Other environmental parameters can also be monitored, e.g., relative humidity and temperature. Generally, one or more sensors can be accommodated within the same SN enclosure, with each sensor measuring one of the mentioned parameters. The SNs transmit the measured data to the BS using the presented communication protocol. SNs can communicate directly with the BS. Another scenario is to communicate with a nearby relay node (RN) using limited power, and the RN would relay the data to the BS wirelessly, or to the data center containing the database server using the wired network. The most challenging scenario is in the case of collaboration between the nodes (in case of very high density of small SNs), where the nodes can form cooperative clusters, and relay the data in a multihop fashion ensuring energy efficiency. The presented protocol is applicable to these scenarios. However, in scenarios with RNs or multihop communications, the protocol is applicable at the last hop for communication with the BS.

2) The database server: the monitoring data received at the BS is sent to a database server. There, it can be in a common format which would facilitate data extraction and analysis. The measurement data could contain missing, noisy, or erroneous values. Appropriate data processing techniques and integrity checks are generally performed before storing the data for

subsequent use. Afterwards, the data becomes ready for analysis and display. Several tools can be used by experts for data analysis, e.g., statistics (for computation of daily, monthly, or yearly averages of a certain air pollutant), advanced interpolation, neural networks, principal component analysis, and data mining techniques.

3) The Client tier: it consists of client-side applications. They can be running on computers or mobile devices, e.g. smart phones. They access the network via the server, which forwards the pollution information stored in the database in an appropriate format after performing necessary processing if needed. Typical applications could consist of web sites that are periodically updated with data summaries and statistics, data visualization showing the locations of SNs on a map along with their instantaneous measurements and/or measurement history, and other data dissemination applications, e.g., SMS alerts that inform the population of the gravity of pollution levels in certain areas.

A typical system model for air pollution monitoring is shown in Fig. 6. In this model, a cell of certain area can be served by a BS, and several SNs are deployed to monitor environmental parameters in each cell.

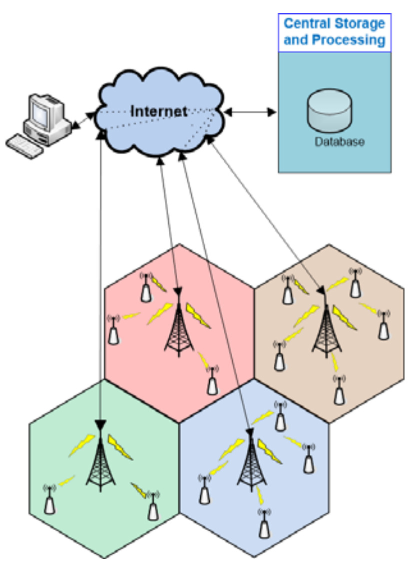


Fig. 6. Implementation scenario for air pollution monitoring.

### *4.2 Simulation Results: Implementation of the OFDMA Aloha Approach in the Air Pollution Detection WSN*

In the simulations, we consider a single BS with SNs uniformly distributed within its coverage area. The total bandwidth considered is $B = 5$ MHz, subdivided into 25 subchannels of 12 subcarriers each (3GPP TS 36.211; 3GPP TS 36.213; Lunttila et al., 2007). Up to 30 SNs are considered in each cell, which is reasonable with the cell sizes considered in the following subsections. In addition, the SNs represent the nodes communicating directly with the BS. As explained previously, in the case where they are relaying other SNs data via multihop, the actual number of SNs in the cell would be larger.

#### *4.2.1 Results with Different Transmission Probabilities.*

In this section, a cell radius of 500 m is considered and a target rate of 128 kbps is assumed for SNs. The impact of varying the transmission probability is studied. The case of constant transmission probabilities $p_T(k, i) = p_T$, while setting $p_T = 0.2$, $p_T = 0.5$, and $p_T = 0.7$, is compared to the case of dynamic transmission probability according to Eq. (11). In the dynamic scenario, $p_{T0} = 0.9$ is used in order to increase the probability of selecting the subchannels having the best channel gain for transmission.

The collision probability results are displayed in Fig. 7. It can be noted that for fixed $p_T$, reservations become more aggressive as $p_T$ increases. This leads to a slight increase in collision probability, but the results remain comparable for the three values considered in the fixed $p_T$ scenario. However, the performance of the dynamic scheme is significantly better, since this scheme intelligently exploits the frequency diversity.

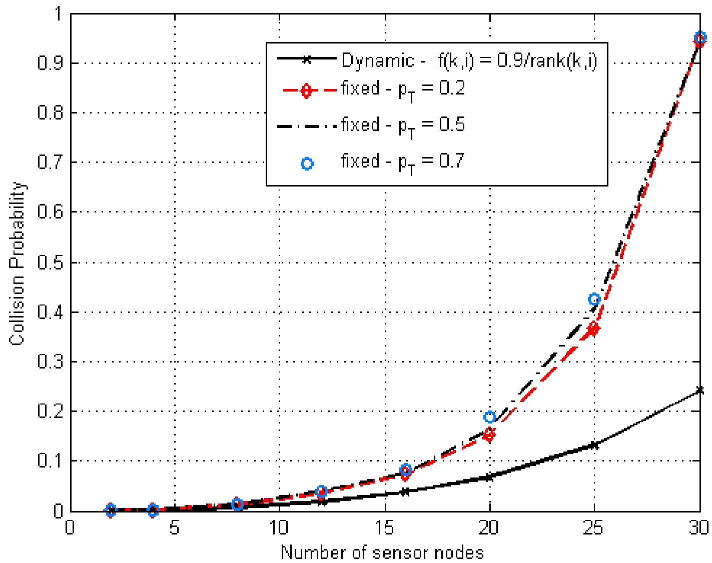


Fig. 7. Collision probability of the proposed scheme for a target rate of 128 kbps, a cell radius of 500 m and different values of the transmission probability.

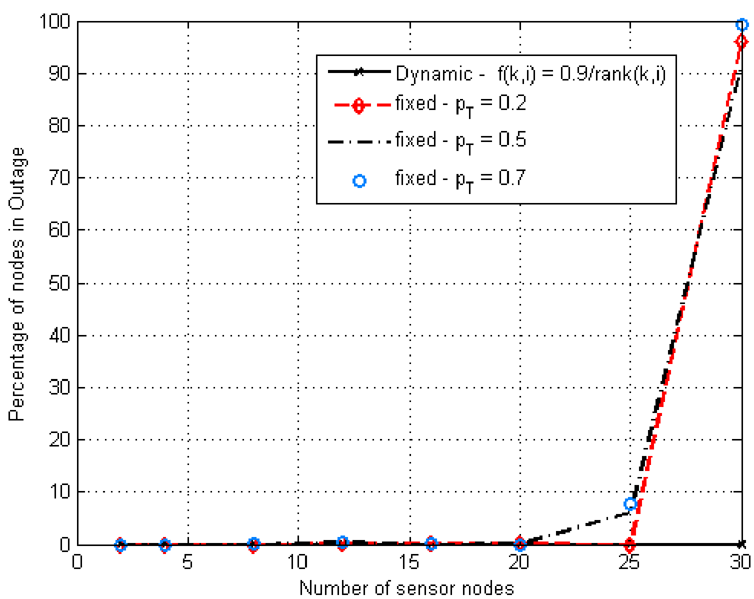


Fig. 8. Percentage of SNs in outage of the proposed scheme for a target rate of 128 kbps, a cell radius of 500 m and different values of the transmission probability.

Fig. 8 shows the outage results. In all the investigated scenarios, when the number of SNs is 25 or lower, the percentage of SNs in outage can be considered to be negligible. An increase of the number of SNs to 30 SNs in the cell leads to unstable results with the cases having $p_T = 0.2$, $p_T = 0.5$, and $p_T = 0.7$, since they lead to 96.13, 91.53, and 99.33% of SNs in outage, respectively. The dynamic approach has a remarkable performance with 0% of SNs in outage for all the simulated values. The sum-rate results, presented in Fig. 9, show a comparable performance for all the studied cases when the number of SNs is less than 25. When this number exceeds 25 SNs, the superiority of the dynamic scheme becomes evident, since it has no SNs in outage. In fact, with the dynamic scheme, all SNs achieve their target rate (0% outage), which leads to a sum-rate of 3.93 Mbps, compared to 2.16 Mbps for the case $p_T = 0.5$, where a high outage rate is achieved.

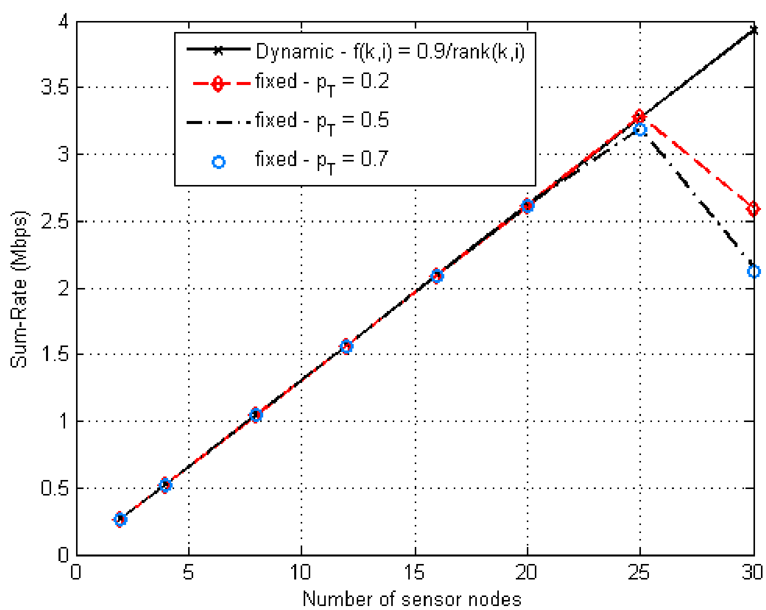


Fig. 9. Rate of the proposed scheme for a target rate of 128 kbps, a cell radius of 500 m and different values of the transmission probability.

The change in performance at the threshold of 25 SNs can actually be explained by the fact that the simulation parameters assume the existence of 25 subchannels. Thus, with the fixed probability schemes, when the number of SNs exceeds the available number of subchannels, it becomes difficult to achieve the target rates for all SNs. However, with the dynamic approach, SNs can successfully transmit their data even when their number exceeds the number of available subchannels, due to the intelligent use of the channel state information by the dynamic scheme.

*4.2.2 Results with Different Target Rates.*

Simulation results for a cell radius of 500 meters and three different target rates: 64 kbps, 128 kbps, and 256 kbps are presented in this section. A constant $p_T = 0.5$ is used. The sum-rate results, the percentage of SNs in outage, and the collision probability results are shown in Figs. 10-12, respectively. When the number of SNs is small (up to four SNs), the investigated schemes perform comparably. In addition, all SNs achieve their target data rate. However, as soon as the number of SNs increases, the TDMA approach and the FDMA approach degrade significantly, whereas the proposed scheme shows better performance when the number of SNs increases.

Using the proposed scheme with $R_T = 64$ kbps, all the SNs are successfully transmit their data even when the number of SNs reaches 30. With $R_T = 128$ kbps, performance degrades when the number of SNs exceeds 25. With $R_T = 256$ kbps, the degradation is noted when the number of SNs exceeds 20. Indeed, an increasing number of SNs and/or target data rate increases imply that more packets should be transmitted at the same time in order to achieve the target data rate for all SNs. Consequently, this is expected to lead to an increase in collision probability during the reservation phase, as shown in Fig. 12. Thus, fewer transmissions occur during the transmission phase, hence reducing the sum-rate, as shown in Fig. 10. A straightforward consequence is the increase of the number of SNs in outage, as shown in Fig. 11.

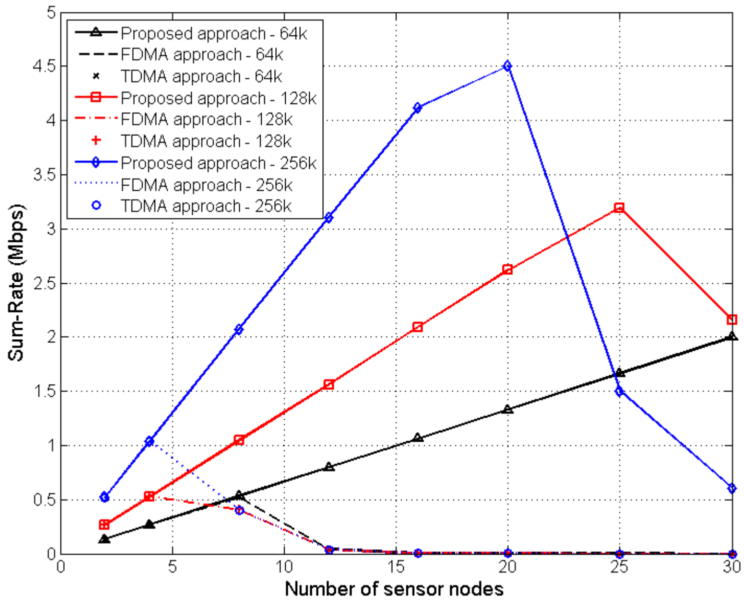


Fig. 10. Sum-rate of the compared methods for a cell radius of 500 m and different target rates.

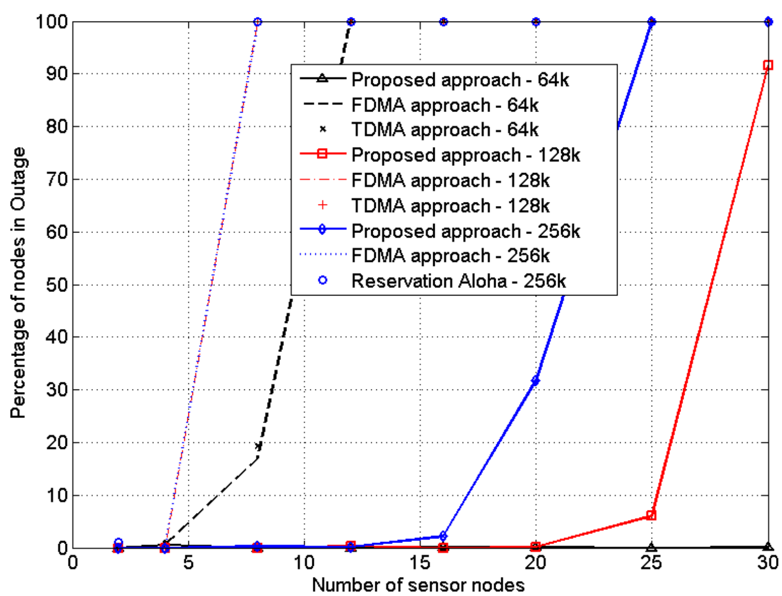


Fig. 11. Percentage of SNs in outage for a cell radius of 500 m and different target rates.

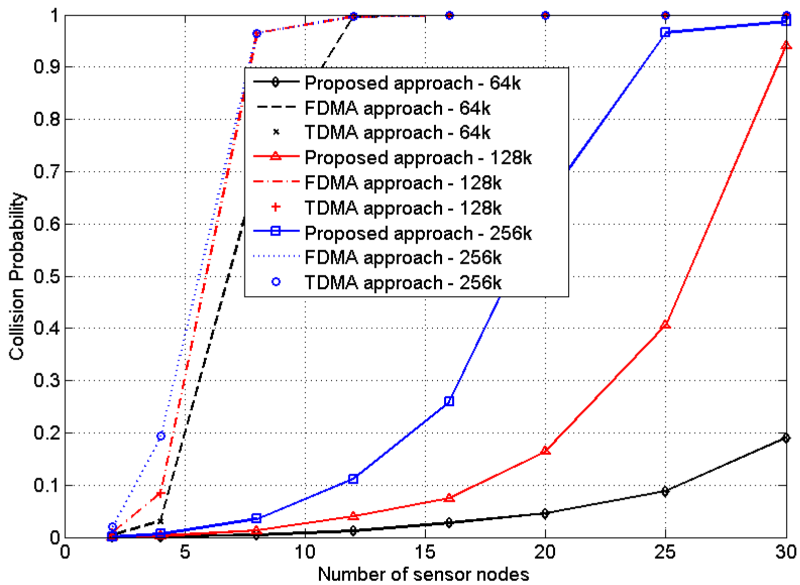


Fig. 12. Collision probability of the different schemes for a cell radius of 500 m and different target rates.

*4.2.3 Results with Different Cell Radii.*

This section presents simulation results for a target rate of 128 kbps and three different values for the cell radius: 250 m, 500 m, and 1000 m. A constant $p_T = 0.5$ is used in this section. Figs. 13-15 show the sum-rate results, the percentage of SNs in outage, and the collision probability results, respectively. Naturally, an increase in the distance leads to a significant reduction in the SNR received at the BS, which reduces the achievable rate within a reserved time slot. However, the proposed scheme outperforms the other schemes and achieves the target rate when the distance increases, for a relatively small number of SNs. In fact, in this case, enough time slots are available with the proposed scheme to compensate the increase in the distance, although each SN would require a higher number of time slots to compensate the increased distance. When the number of SNs increases, more collisions will occur in the reservation phase, as shown in Fig. 15, which leads to fewer transmissions in the transmission phase, thus reducing the achieved rate, as shown in Fig. 13, and increasing the number of SNs in outage, as shown in Fig. 14.

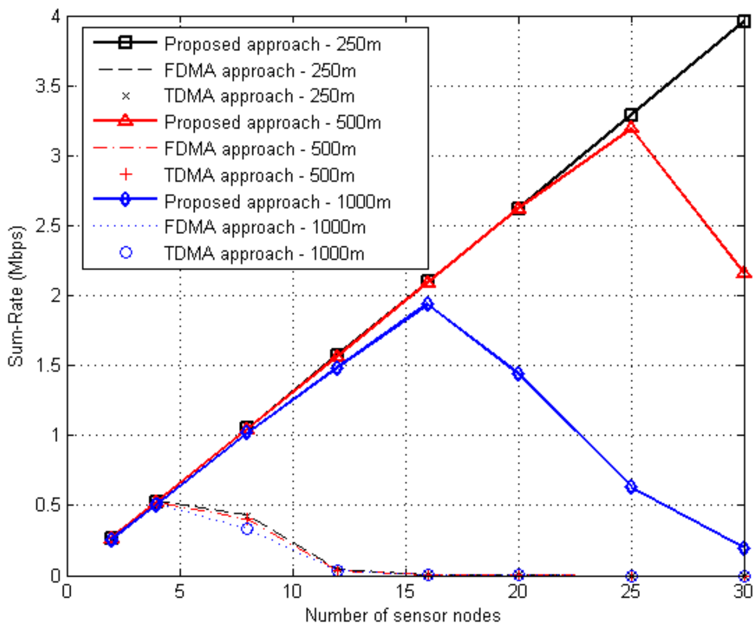


Fig. 13. Sum-rate of the different schemes for a target rate of 128 kbps and different values of the cell radius.

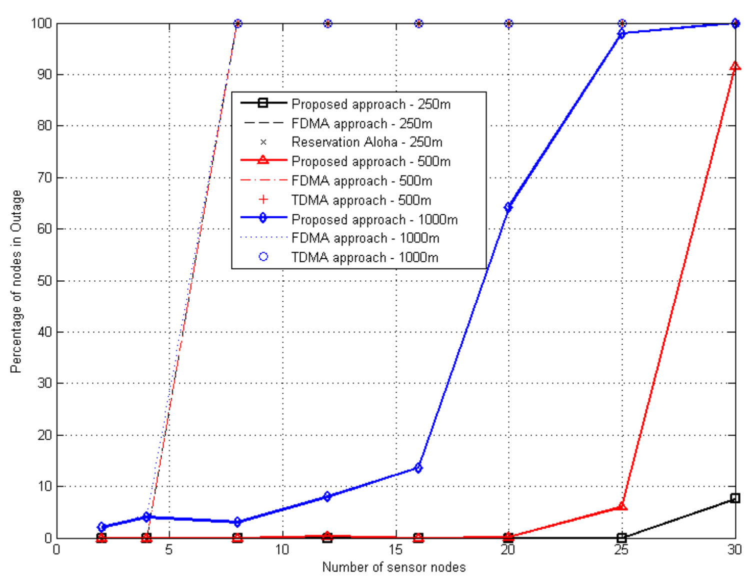


Fig. 14. Percentage of SNs in outage for a target rate of 128 kbps and different values of the cell radius.

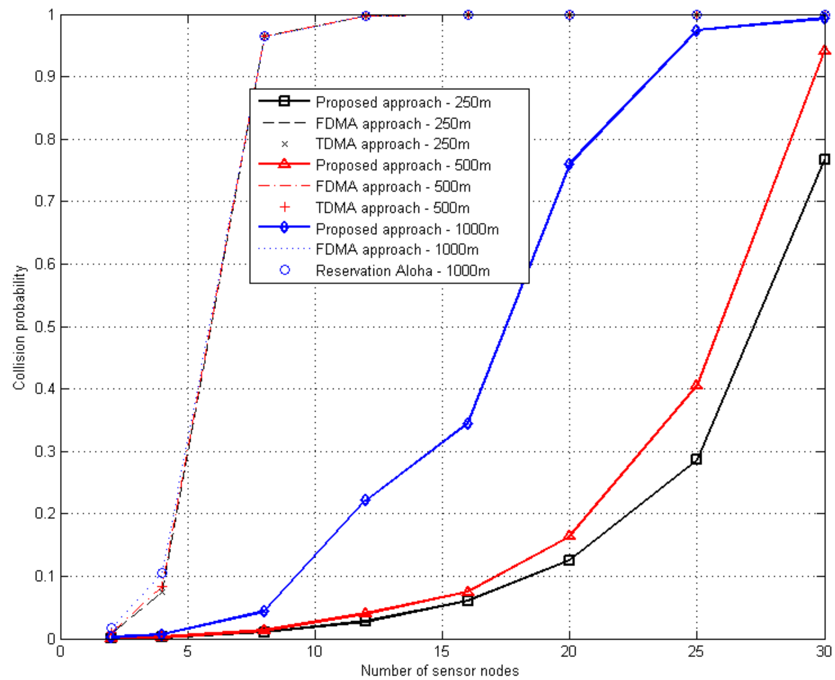


Fig. 15. Collision probability of the different schemes for a target rate of 128 kbps and different values of the cell radius.

### *4.3 Implementation Challenges*

Despite its superior performance, there are some implementation issues and tradeoffs that should be taken into account while implementing the proposed approach.

An important challenge is to maintain accurate synchronization. Although this is largely facilitated by periodically transmitting a pilot sequence by the BS, the SNs still have to be able to determine the boundaries of the small reservation slots over all available subcarriers. In addition, although the number of available subcarriers might be limited at a given time due to being used for more "traditional" cellular traffic, SNs still have to be able to "listen" to all subcarriers, since the set of subcarriers that are "free" for SN transmission will naturally vary with time. Another challenge is to appropriately determine the transmission probabilities in an optimized way that allows serving the largest possible number of SNs. Finally, the “possible” implementation in an LTE system proposed in this chapter is not possible without successful standardization, and then successful implementation by equipment manufacturers.

## 5. Conclusions and Future Work

A communication protocol for WSNs was presented and analyzed. It is based on OFDMA, and allows the SNs to estimate the CSI on the various subchannels. Thus, they can perform independent subchannel reservation based on random access. The presented approach was investigated in the context of WSNs for air pollution monitoring. It was shown to lead to increased data rates and reduced collisions. Furthermore, collisions occur during the reservation phase, but not during the transmission phase, which avoids unnecessary wasted power due to colliding transmissions, thus leading to energy savings much needed in WSNs.

Although current communication techniques like GPRS and HSPA can be used with WSNs, the network is expected to be quickly congested in an IoT scenario when the number of SNs transmitting over the cellular system increases. On the other hand, the presented approach is based on OFDMA, and thus could be implemented in conjunction with state-of-the-art wireless communication systems, e.g., LTE/LTE-Advanced. For example, the APs of the presented protocol could be co-located with cellular BSs (e.g. LTE BSs), which could inform the WSN AP of the occupied subchannels within its cell, and the AP would transmit pilot signals only on the available (free) subchannels. Then, SNs would apply the presented approach to dynamically share these free subchannels, without impacting the primary cellular traffic in the network.

Future work consists of studying the feasibility of incorporating the proposed method in standardization releases relevant to IoT/Cyber-Physical systems. Furthermore, it would be interesting to study variations of the proposed approach that might be more suitable to specific IoT scenarios. For example, in the scenario of (near) real-time smart meter reading, or in the studied scenario of air pollution monitoring with periodic transmission of sensor data, the locations of IoT devices, and the time of their scheduled transmissions, are generally known in advance. Pre-scheduling or preliminary resource allocation can be performed in conjunction with the proposed approach to avoid collisions even in the reservation phase. For general scenarios, or for unscheduled transmissions, e.g., a pollution monitoring sensor raising an alarm before its periodic transmission time, the proposed approach remains applicable as is. Another important area for future study is the implementation of security and privacy techniques in conjunction with the proposed approach. Last but not least, an interesting research area would be to benefit from the large antenna arrays in massive MIMO systems in order to combine spatial diversity and/or beamforming (at the BS) with the proposed approach in order to successfully accommodate the largest possible number of SNs while avoiding to increase the feedback overhead on these SNs.

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