Enabling Smart Grid via TV White Space Cognitive Radio

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***Abstract*—The attractive characteristics of the TV White Space makes it the ideal candidate for enabling multiple and independently-operated secondary networks via Cognitive Radio paradigm. However, so far, there are no regulatory requirements for the coexistence among heterogenous secondary networks over TVWS. Hence, their mutual interference can be very severe. This issue is even more crucial in urban Smart Grid scenarios, where the latency and energy requirements are very tight and multiple Neighborhood Area Networks (NANs) are likely to be located within the same geographical area. Hence, in this paper, the problem of the interference among multiple NANs is addressed with the objective to maximize the achievable data rate. To this aim, the Gateway senses the TVWS channel declared available from incumbents by the WSDB to discover the presence of an interfering NAN. If the sensing declares the TVWS channel as idle, the Gateway can transmit over such a channel. Otherwise, the Gateway uses the ISM channel. Within the paper, the choice of the sensing duration maximizing the achievable data rate at the Gateway, by explicitly accounting for the accuracy/overhead trade-off and the co-located NANs traffic patterns, is addressed. Numerical results validate the theoretical analysis.**

***Index Terms*—smart grid, cognitive radio; channel outage, TV white space**

I. Introduction

Regulatory efforts are currently ongoing in many countries to enable secondary (unlicensed) access [1], [2] to the TV White Space (TVWS) spectrum. The existing rulings [3]–[5] obviate the spectrum sensing [6] as the mechanism for the Secondary Networks (SNs) to determine the TVWS availability at their respective locations. Instead, they require the SNs to periodically access to a geolocated database, referred to as White Space DataBase (WSDB) for acquiring the list of TVWS channels free from incumbents.

The introduction of a simple mechanism for incumbent protection along with the excellent TVWS propagation characteristics makes the TVWS spectrum highly desirable when either the ISM spectrum propagation or the ISM bandwidth do not comply with the scenario requirements. Hence, TVWS spectrum is the ideal candidate for enabling Smart Grid technologies to design more efficient ways to manage power supply/demand [7]–[9], as well as to provide broadband internet access to underserved areas.

Let us consider a typical urban Smart Grid scenario shown in Figure 1, where several Smart Meters connected to a Gateway constitutes an Home Area Network (HAN), and multiple Gateways connected to a Data Aggregate Unit (DAU) constitute a Neighborhood Area Network (NAN) [10]. The Gateway is responsible for transmitting the meter data periodically collected within its HAN to the DAU. The Gateway can route the meter data to the DAU either through a TVWS channel, once declared available by the WSDB, or through an ISM band. The Gateway would benefit from using the TVWS spectrum over the ISM spectrum due to its attractive characteristics. However, since experimental studies have shown that the TVWS spectrum is significantly scarce in urban areas [11], [12], it is likely that multiple closely-located NANs are authorized to use the same TVWS channel and may create interference to each other, leading so to a performance degradation.

Furthermore, it is envisioned that, in the near future, multiple heterogeneous and independently-operated SNs will exploit the TVWS spectrum within the same geographical area [13]. So far, there are no regulatory requirements for the coexistence among heterogenous SNs over TVWS. Hence, the interference on the TVWS channel between the Gateway and the DAU can become even more severe.

In this paper, we address this issue with the object to maximize the achievable data rate at the Gateway. To this aim, we propose to allow the Gateway to sense the TVWS channel declared available from incumbents by the WSDB to discover the presence of an interfering NAN. If the sensing declares the TVWS channel as idle, the gateway can transmit over such a channel. Otherwise, the gateway uses the ISM channel. The longer is the sensing duration, the higher is the sensing accuracy but the higher is the sensing overhead. Hence, within the paper, we focus on choosing the sensing duration maximizing the achievable data rate at the Gateway, by explicitly accounting for the accuracy/overhead trade-off and for the traffic patterns of the interfering NANs. To this aim, we derive the closed-form expression of the expected data rate.

The rest of the paper is organized as follows. In Section I-A we discuss the related works. In Section II, we describe the

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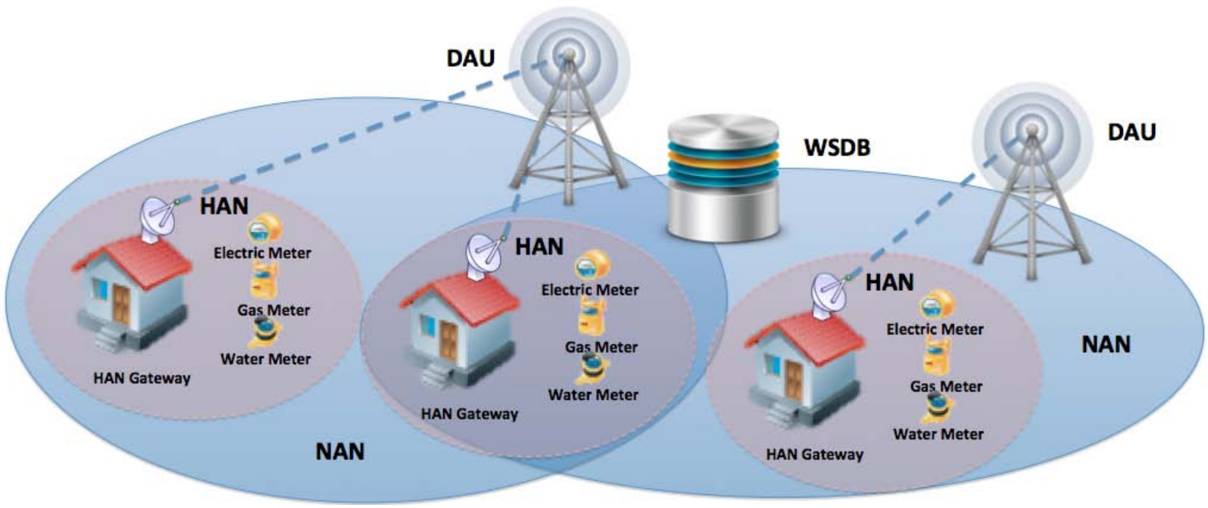

Fig. 1. TVWS Smart Grid Scenario: NANs coexisting within the same geographical area can cause interference each others due to the excellent propagation characteristics of the TVWS spectrum.

system model. In Section III, we derive the sensing time value maximizing the expected data rate, and we validate the analytical results in Section IV. Finally, in Section V, we conclude the paper.

A. Related Works

Very recently, the adoption of the Cognitive Radio (CR) paradigm for designing Smart Grid communications has gained a lot of attention. In [10] the authors analyze the impact of the channel outage on the Demand/Response Management (DRM) control performance, by proposing a cognitive-based two-way communication switching procedure to reduce the channel outage. In [14] the authors carry out a study on a two-way cognitive-based switching procedure, by evaluating the sensing-time maximizing the transmission opportunities under a sensing accuracy constraint. Unlikely all the cited papers, in this work the peculiar and unique properties of the TVWS are taken into account. Specifically, as mentioned in the introduction, we consider the presence of multiple closely-located NANs that are authorized by a WSBD to use the same TVWS channel, by creating so interference to each other and hence performance degradation. The object is to maximize the achievable data rate at the Gateway.

II. System Model

We consider the Smart Grid scenario depicted in Figure 1. Specifically, several Smart Meters connected to a Gateway constitute a Home Area Network (HAN), with the Gateway responsible for transmitting the meter data periodically collected within its HAN to the Data Aggregate Unit (DAU). Multiple Gateways connected to a DAU constitute a Neighborhood Area Network (NAN). Each HAN Gateway is equipped with a single[1] radio interface operating either: i) within an ISM channel, freely; ii) within a TVWS channel, once authorized by the White Space DataBase (WSDB) as required by the current regulations and standards [3], [4], [15], [16]. As mentioned in Section I, the TVWS spectrum is preferred over the ISM spectrum due to its distinctive characteristics, such as the excellent propagation [17]. However, since experimental studies have shown that the TVWS spectrum is significantly scarce in urban areas [11], it is likely that multiple closely-located NANs are authorized to use the same TVWS channel, causing so interference each other. Hence, a gateway aiming at maximizing the achievable data rate must assess the presence of an interfering signal by sensing the TVWS channel for a certain amount of time, say τ. If the sensing declares the TVWS channel as available, the gateway can transmit over such a channel. Otherwise, the gateway uses the ISM channel.

[1]Such an assumption is reasonable since low cost is a strong requirement for the Gateways, whereas it is reasonable to assume a DAU equipped with multiple network interfaces [9].

III. Data Rate Maximization

At first, we give some preliminaries that will be used through the paper.

Assumption 1. The gateway time is organized into fixed-size time slots of duration T. The *sensing time* τ is the portion of T devoted to the TVWS channel sensing, whereas the *transmission time* $T_{\text{tx}} \triangleq T - \tau$ is the portion of T devoted to transmission.

Remark. The lower is the sensing time τ, the higher is the portion of T devoted to transmission, i.e., the lower is the sensing overhead.

Definition 1. (Detection Probability) The *detection probability* $P_{\text{d}}(\tau)$ is the probability of the TVWS channel being sensed as unavailable given that at least one closely-located NAN is transmitting over the same TVWS channel, and by adopting an energy detection[2] it results [10]:

$$P_{\text{d}}(\tau) = Q\left(\sqrt{W\tau}\left(\frac{\varepsilon}{2W\tau(\gamma+1)} - 1\right)\right) \tag{1}$$

where $Q(\cdot)$ denotes the Q-function, W is the signal bandwidth, γ is the Signal-to-Noise Ratio (SNR) at the considered gateway transceiver, ε is the detector threshold normalized to the mean square of the additive white Gaussian noise σ^2.

Detection Probability Constraint. The lower is the sensing time, the lower is the detection probability $P_{\text{d}}(\tau)$, hence the higher is the interference caused to closely-located NANs transmitting on the same TVWS channel. Hence, it is reasonable to impose a constraint on the detection probability:

$$P_{\text{d}}(\tau) \geq P_{\text{d}}^{\text{min}} \tag{2}$$

with $P_{\text{d}}^{\text{min}}$ depending on the Smart Grid requirements.

Definition 2. (False-Alarm Probability) The *false-alarm probability* $P_{\text{fa}}(\tau)$ is the probability of the TVWS channel being sensed as unavailable given that no closely-located NAN is transmitting over the same TVWS channel, and by adopting an energy detection it results [10]:

$$P_{\text{fa}}(\tau) = Q\left(\sqrt{W\tau}\left(\frac{\varepsilon}{2W\tau} - 1\right)\right) \tag{3}$$

Remark. The higher is the false-alarm probability $P_{\text{fa}}(\tau)$, the higher is the amount of TVWS communication opportunities lost.

Definition 3. (Channel Outage Probability) The *channel outage probability* is the probability of a channel being in the outage state, i.e., being unavailable due to adverse wireless propagation conditions. In the following, we denote with $P_{\text{O}}^{\text{ISM}}$ and P_{O}^{TV} the outage probability for the ISM channel and the TVWS channel, respectively.

Definition 4. (Switching Probability) Given the sensing time τ, the *switching probability* $P_{\text{SW}}(\tau)$ is the probability of the TVWS channel being declared as available by the sensing procedure:

$$P_{\text{SW}}(\tau) = P_1\left(1 - P_{\text{d}}(\tau)\right) + P_0\left(1 - P_{\text{fa}}(\tau)\right) \tag{4}$$

where P_1 denotes the probability of at least one closely-located NAN transmitting over the same TVWS channel, $P_0 \triangleq 1 - P_1$, and $P_{\text{d}}(\tau)$ and $P_{\text{fa}}(\tau)$ denote the detection and the false-alarm probability of the sensing procedure, respectively.

Remark. According to (4), a switching event occurs if either: i) the TVWS channel is available and the sensing process correctly decides; ii) the TVWS channel is busy and the sensing process fails. We note that the *switching probability* depends on: i) the traffic patterns of the closely-located NANs sharing the same TVWS channel, through probability $P_1(\tau)$; ii) the sensing accuracy, through the probabilities $P_{\text{d}}(\tau)$ and $P_{\text{fa}}(\tau)$; iii) the sensing time τ.

[2]This is reasonable in a Smart Grid scenario due to its lowest complexity and a-priory knowledge requirement [9].

Definition 5. (Outage Probability) Given the sensing time τ, the *outage probability* $P_{\text{O}}(\tau)$ is the probability of the Gateway being unable to communicate with the DAU:

$$\begin{aligned} P_{\text{O}}(\tau) &= \left(1 - P_{\text{SW}}(\tau)\right) P_{\text{O}}^{\text{ISM}} + P_{\text{SW}}(\tau) P_{\text{O}}^{\text{TV}} = \\ &= \left(P_{\text{O}}^{\text{TV}} - P_{\text{O}}^{\text{ISM}}\right) P_{\text{SW}}(\tau) + P_{\text{O}}^{\text{ISM}} \end{aligned} \tag{5}$$

Remark. According to (5), an outage event occurs if either: i) a switching event does not occur and the ISM channel is outage; ii) a switching event occurs and the TVWS channel is outage.

Outage Probability Constraint. Since[3] $P_{\text{O}}^{\text{TV}} < P_{\text{O}}^{\text{ISM}}$, from (5) it results $P_{\text{O}}^{\text{TV}} < P_{\text{O}}(\tau) < P_{\text{O}}^{\text{ISM}}$ for any value of τ. Consequently, by choosing to use both the ISM and the TVWS spectrum instead of using only the ISM spectrum we are able to reduce the outage events, improving so the Smart Grid communications reliability. Hence, it is reasonable to impose a constraint on the outage probability:

$$P_{\text{O}}(\tau) \leq P_{\text{O}}^{\text{min}} \tag{6}$$

with $P_{\text{O}}^{\text{min}} > P_{\text{O}}^{\text{TV}}$ in order to have an achievable constraint, and this implies . This constraint

Definition 6. (Expected Data Rate) Given the sensing time τ, the *expected data rate* $R(\tau)$ denotes the expected data rate achievable by the Gateway during an arbitrary time slot.

Remark. The considerations made so far suggest that a performance metric able to account for the trade-off between the advantages gained by increasing the sensing accuracy with longer sensing times and the induced overhead is needed. Clearly, the expected data rate satisfies such a requirement by measuring the average throughput available at each Gateway.

Optimization Problem. The goal is to choose the sensing time τ^* that jointly: i) maximizes the expected data rate $R(\tau)$; ii) satisfies the outage probability constraint $P_{\text{O}}^{\text{min}}$:

$$\tau^* = \underset{\tau \in \mathcal{R}_0^*}{\text{argmax}} \left\{R(\tau)\right\} \tag{7}$$

$$\text{subject to:} \quad P_{\text{O}}(\tau) \leq P_{\text{O}}^{\text{min}}$$

In order to derive the closed-form expression of the expected data rate $R(\tau)$, Lemmas 1 and 2 (based on Eq. 2.10-2.11 in [14]) are required.

Lemma 1. ***(Switching Probability)*** *Given the sensing time τ, the switching probability $P_{SW}(\tau)$ satisfying the detection probability constraint P_d^{min} is given by:*

$$\begin{aligned} P_{SW}(\tau) =& 1 - P_1 P_d^{\text{min}} - \\ & - P_0 Q\left(\gamma\sqrt{W\tau} + Q^{-1}(P_d^{\text{min}})(\gamma+1)\right) \end{aligned} \tag{8}$$

[3]Such an assumption is justified by considering the excellent propagation characteristics of the TVWS spectrum with respect to the ISM spectrum traditionally used in wireless communications, i.e., 915MHz, 2.4GHz or 5.8 GHz.

Remark. By accounting for the decreasing property of the Q-function, it results that $P_{\text{fa}}(\tau)$ decreases as τ increases. Hence, the minimum false-alarm probability is given by:

$$P_{\text{fa}}^{\min} = P_{\text{fa}}(T) = = Q\left(\gamma\sqrt{WT} + Q^{-1}(P_{\text{d}}^{\min})(\gamma+1)\right] \quad (9)$$

Lemma 2. ***(Outage Probability)*** *Given the sensing time τ, the outage probability $P_O(\tau)$ satisfying the detection probability constraint P_d^{min} is given by:*

$$P_O(\tau) = \left(P_O^{TV} - P_O^{ISM}\right) Q\left(\gamma\sqrt{W\tau} + Q^{-1}(P_d^{\min})(\gamma+1)\right) + + \left(P_O^{TV} - P_O^{ISM}\right) P_1 P_d^{\min} + P_O^{ISM} \quad (10)$$

Remark. As τ increases, $P_{\text{SW}}(\tau)$ (8) approaches its maximum value $1 - P_1 P_{\text{d}}^{\min}$ while $P_{\text{O}}(\tau)$ (10) approaches its minimum value $\left(P_{\text{O}}^{\text{TV}} - P_{\text{O}}^{\text{ISM}}\right) P_{\text{SW}}^{\min} + P_{\text{O}}^{\text{ISM}}$. However, as τ increases, the portion of T devoted to packet transmission decreases.

Remark. From (10), the outage probability constrained $P_{\text{O}}(\tau) \leq P_{\text{O}}^{\min}$ is satisfied if it results $\tau \geq \tau_{min}$, with:

$$\tau_{\text{min}} = \frac{1}{\gamma^2 W}\left(-Q^{-1}(P_d^{\min})(\gamma+1) + +Q^{-1}\left(\frac{P_{\text{O}}^{\min} - (P_{\text{O}}^{\text{ISM}} - P_{\text{O}}^{\text{TV}})P_1 P_d^{\min} - P_{\text{O}}^{\text{TV}}}{(P_{\text{O}}^{\text{ISM}} - P_{\text{O}}^{\text{TV}})P_0}\right)\right)^2 \quad (11)$$

Theorem 1. ***(Expected Data Rate)*** *Given the sensing time τ, the expected data rate $R(\tau)$ is equal to:*

$$R(\tau) = C^{ISM}(1 - P_O^{ISM})\left(P_1 P_d(\tau) + P_0 P_{fa}(\tau)\right)(1 - \tau/T) + + C^{TV}(1 - P_O^{TV})P_0\left(1 - P_{fa}(\tau)\right)(1 - \tau/T) \quad (12)$$

where C^{TV} and C^{ISM} denotes the capacity of the ISM and the TVWS channel, respectively.

Proof: The Gateway uses the ISM channel if either: i) with probability $P_1 P_d(\tau)$ the TVWS channel is busy and the sensing process correctly decides; ii) with probability $P_0 P_{fa}(\tau)$ the TVWS channel is available but a false-alarm event occurs. In both the cases, the Gateway can transmit over the ISM channel with probability $(1 - P_O^{ISM})$, and the fraction of time devoted to packet transmission is $1 - \tau/T$. Differently, the Gateway uses the TVWS channel if either i) with probability $P_1(1 - P_d(\tau))$ the TVWS channel is busy but a missing-detection event occurs; ii) with probability $P_0(1 - P_{fa}(\tau))$ the TVWS channel is available and the sensing process correctly decides. However, only the latter event contributes to the data rate, since during the former event the packet transmission fails due to interference. Hence, the thesis follows. ■

By accounting for Theorem 1, we can reformulate the optimization problem in (7) as follows.

Reformulated Optimization Problem. The goal is to choose the sensing time τ^* that jointly: i) maximizes the expected data rate $R(\tau)$; ii) satisfies the outage probability constraint $P_{\text{O}}^{\min}$, as shown at the top of the next page.

IV. Numerical Evaluation

In this section, we evaluate the performance of the proposed optimization by adopting, as a case study, a Smart Grid based on IEEE 802.11af wireless technology for the TVWS channels and on IEEE 802.11b[4] wireless technology for the ISM bands. The simulation set is as follows. The channel outage probabilities $P_{\text{O}}^{\text{ISM}}$ and P_{O}^{TV} are equal to 0.04 and 0.02, respectively. The detection probability constrained $P_{\text{d}}^{\min}$ is equal to 0.95, while the probability P_1 of at least one closely-located NAN transmitting over the same TVWS channel is equal to 0.4. By adopting 6MHz wide TVWS channels, the channels capacities C^{ISM} and C^{TV} are equals to 11 and 26.7MBps, respectively. Finally, the time slot duration T is equal to 300μs.

In Figure 2, we report the sensing time as a function of the SNR γ at the considered gateway transceiver. Specifically, we report three curves: i) the sensing time τ^{r} maximizing the data rate $R(\tau^*)$ (12); i) the sensing time τ_{min} satisfying the outage probability constrained (11); iii) the sensing time τ^* jointly maximizing the data rate and satisfying the outage probability constrained. At first, we observe that, for the lowest values of γ, the sensing time τ^{r} increases as γ increases. This is reasonable since the benefits provided by larger sensing times in terms of sensing accuracy, i.e., detection events, dominate the overhead induced by the sensing process. Once a threshold value of γ is reached, the sensing time τ^{r} decreases as γ increases since the overhead induced by the sensing process dominates the sensing benefits. Furthermore, we note that $\tau^{\min}$ increases as γ increases. This behavior is reasonable and in agreement with (13).

In Figure 3, we report the achievable data rate as a function of the SNR γ transceiver. Specifically, we report three curves: i) the data rate $R(\tau^*)$ given in (12); ii) the data rate $R^{\text{ISM}} = (1 - P_{\text{O}}^{\text{ISM}})C^{\text{ISM}}$ achievable by using only the ISM band; iii) the data rate $R^{\text{TV}} = (1 - P_{\text{O}}^{\text{TV}}) \cdot P_0 C^{\text{TV}}$ achievable by using only the TV band. We observe that the data rate $R(\tau^*)$ exhibits a concave behavior. This agrees with the comments made for the previous figure.

V. Conclusions

In this paper we studied the problem of the interference in TVWS-enabled urban Smart Grid scenarios. Specifically, the objective of the paper is to maximize the achievable data rate of an arbitrary Neighborhood Area Networks (NAN) subject to interference caused by NANs located within the same geographical area and authorized to use the same TVWS channel. For this, we proposed to allow the Gateway to sense the TVWS channel declared available from incumbents by the WSDB to discover the presence of an interfering NAN. If the sensing declares the TVWS channel as idle, the Gateway can transmit over such a channel. Otherwise, the Gateway uses the ISM channel. Clearly, the sensing of the interfering NANs affects the performance of the considered NAN, hence within the paper, we design the sensing duration that maximizes

[4]It is well known that IEEE 802.11b provides larger transmission ranges with respect to higher-throughput standard versions, such as IEEE 802.11g/n.

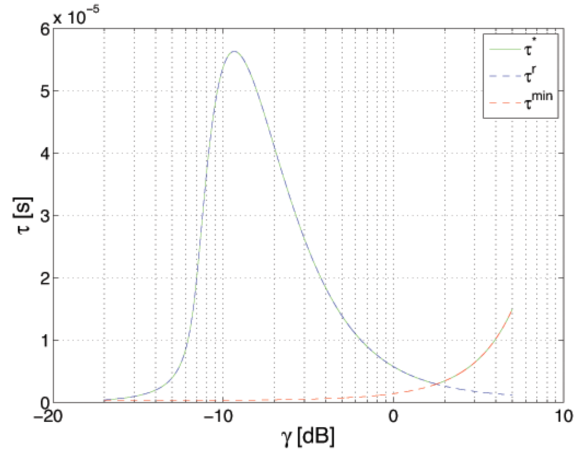

Fig. 2. Sensing Time vs SNR γ.

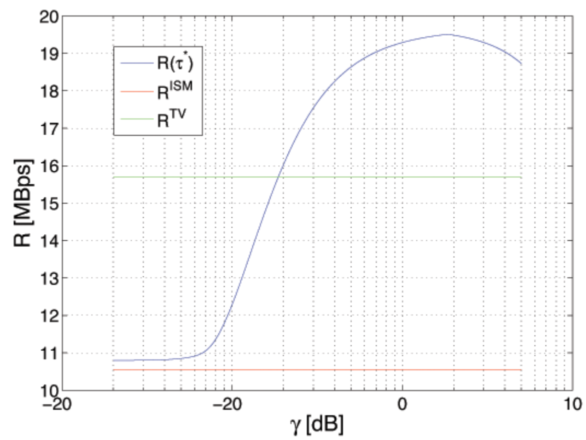

Fig. 3. Achievable Data Rate vs SNR γ.

$$\tau^* = \underset{\tau \in \mathcal{R}_0^*}{\operatorname{argmax}} \left\{ C^{\rm ISM}(1 - P_{\rm O}^{\rm ISM}) \left(P_1 P_{\rm d}(\tau) + P_0 P_{\rm fa}(\tau) \right) (1 - \tau/T) + C^{\rm TV}(1 - P_{\rm O}^{\rm TV}) P_0 \left(1 - P_{\rm fa}(\tau) \right) (1 - \tau/T) \right\} \quad (13)$$

subject to:

$$\tau^* \geq \tau_{\rm min} = \frac{1}{\gamma^2 W} \left(-Q^{-1}(P_d^{\rm min})(\gamma + 1) + Q^{-1} \left(\frac{P_{\rm O}^{\rm min} - (P_{\rm O}^{\rm ISM} - P_{\rm O}^{\rm TV}) P_1 P_d^{\rm min} - P_{\rm O}^{\rm TV}}{(P_{\rm O}^{\rm ISM} - P_{\rm O}^{\rm TV}) P_0} \right) \right)^2$$

the achievable data rate, by explicitly accounting for the accuracy/overhead trade-off and the co-located NANs traffic patterns. Finally, we validated the theoretical analysis through numerical results.

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