Dynamic Spreading Factor Assignment in LoRa Wireless Networks

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***Abstract*—It is vital and challenging to devise new efficient transmission techniques for next generation wireless networks that support internet of things (IoT) systems. Long range (LoRa) wireless networks are based on the deployment of connected devices with limited energy and where end-devices need higher data rates. This system is a key technology that enables smart city applications. The chirp spread spectrum is used as the modulation technique for LoRa networks which consists of assigning various orthogonal spreading factors (SF) among the connected devices in the network. In particular, each device uses a fixed SF for data transmission, which is assigned based on its distance from the gateway. This paper proposes a new SF assignment scheme aiming at enhancing the overall performance. In particular, the proposed scheme no longer assigns SFs based on the distance; but instead, it assigns them depending on the instantaneous channel realizations. Such a dynamic assignment of the SFs among LoRa users significantly enhances the overall performance compared to conventional SF assignment schemes. The proposed system is evaluated in terms of symbol error rate (SER) via numerical simulations.**

***Index Terms*—LoRa networks, SF assignment, symbol error rate.**

I. INTRODUCTION

Long Range (LoRa) network system, which is based on the deployment of large number low-powered connected devices, is key technology for IoT wireless sensor networks that meets the requirement of supporting the exponential growth of connected devices. Indeed, these systems are able to offer sustainable connectivity to low power devices distributed over very large geographical areas. LoRa operates in unlicensed bands and offers adaptive transmission rates and coverage for low-powered devices. Moreover, LoRa network adopts a star-like topology and ALOHA mechanism for channel allocation. These systems outperform conventional cellular and wireless technologies in terms of performance for internet of things (IoT) and emerging smart city applications [1]–[3].

The authors of [4] introduced a new approach to provide connectivity in IoT networks by investigating a long range transmission technology in the unlicensed sub-gigahertz frequency bands. The work in [5] analyzes the functional components of LoRa wireless networks. Specifically, the physical and data link layers performance is analyzed in-depth and evaluated by field tests and simulations. These systems enable long range transfer of information with a low transfer rate. The authors of [6] introduce the modulation scheme underlying LoRa wireless networks, namely, the frequency shift chirp modulation. This scheme is based on coding the information in the frequency shift at the beginning of the symbol. The chirp is assumed to be as a kind of carrier and the modulated signal is a chirp waveform which its behavior depends on a parameter called the spreading factor. The performance of this modulation technique was theoretically investigated. Moreover, the error rate performance of digital chirp communication systems was investigated over various fading channels in [7]. Since the number of devices connected to IoT systems is growing at an exponential rate, the scalability of LoRa networks is investigated in [8] using a stochastic geometry framework. LoRa signals with different SFs are quasi-orthogonal and LoRa signals with the same SF exhibit cross-correlation properties that could make them vulnerable to interference. The conventional LoRa system assigns a higher SF to devices that cover longer distances. However, these systems are limited in terms of spectral efficiency and number of served devices due to the limited number of SFs.

The performance of LoRa networks may be enhanced by adequate resource allocation strategies. Hence, previous efforts have investigated this resource allocation issue under different LoRa network architectures and assumptions. Specifically, SF assignment in LoRa networks were the focus of [9]–[13]. In [9], the authors tried to enhance the network throughput for LoRa systems by proposing a SF allocation strategy based on matching theory. Similarly, the authors of [10] formulate a capacity maximization problem and solved it numerically. In [11], the capacity of a multi-hop LoRa network is improved by an efficient clustering algorithm. In [12], a sub-optimal SF allocation strategy is proposed in order to maximize the packet success probability. In [13], an efficient interference-aware SF allocation algorithm is proposed. However, in these papers, the SF allocation is performed every time period considering only path loss without small-scale fading. It is more efficient but challenging to optimize the SF assignment over each channel realization.

The work in this paper investigates in the SF assignment of multi-device LoRa wireless networks by taken into consideration the channel state information. Specifically, this paper aims to enhance system performance in terms of symbol error rate

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by dynamically assigning the SFs among devices over each channel realization. Simulations are generated and illustrate the performance of the proposed SF assignment algorithm in terms of symbol error rate compared to the conventional LoRa scheme.

The remainder of the paper is organized as follows. The LoRa system model is presented given in Section II. The SF assignment is investigated in Section III. The numerical results are presented and discussed in Section IV. Finally, conclusions are provided in Section V.

II. System Model

In this work, a typical LoRa network is considered that includes a gateway serving K arbitrarily distributed LoRa devices (LDs). The channel coefficients between the gateway and the LD, k, is denoted by $g_k = \beta_k h_k$, where β_k represents the path loss and h_k represents a quasi-static complex Gaussian independent and identically distributed (i.i.d.) slow fading channel. The bandwidth of the channel used for transmission is denoted by B and $T = \frac{1}{B}$ is the duration of a sample transmission.

The LoRa modulation technique is known as the chirp spreading modulation [14]–[16] as shown in Fig. 1. Each LD, k, sends a symbol s_k with duration $T_s = 2^{\alpha_k}T$, where α_k taking values in $\Gamma = \{7, 8, 9, 10, 11, 12\}$ is the corresponding SF for device k [5]. Thus, the k^{th} LD transmits α_k bits at each frame. The symbol s_k takes values in $\{0, 1, 2, \ldots, 2^{\alpha_k} - 1\}$ The LDs adopt different SFs for transmission in order to ensure orthogonality and enable multi-device detection at the receiver. Hence, the transmitted waveform vector for LD, k is given by [6]

$$\mathbf{x}_k = \left[[\frac{1}{\sqrt{2^{\alpha_k}}} e^{j2\pi[(s_k+h) \bmod 2^{\alpha_k}]\frac{h}{2^{\alpha_k}}}]_{h=0\ldots 2^{\alpha_k}-1} \mathbf{0}_{2^{12}-2^{\alpha_k}} \right]^T. \tag{1}$$

Zero padding is added for each vector with length $2^{12} - 2^{\alpha_k}$ in order to ensure the same vector length for all LDs. Hence, the vector of received signals at the LBS is expressed as

$$\mathbf{y} = \sum_{k=1}^{K} g_k \cdot \mathbf{x}_k + \mathbf{w}, \tag{2}$$

where $\mathbf{w}$ is assumed to be additive white Gaussian noise (AWGN) with zero mean and variance σ^2.

When the optimal maximal likelihood (ML) detector is applied at the receiver, the best estimate of the transmitted signal $\hat{s}_k$ by LD k is given over the different signals $\mathbf{c}_{|s_k}$ of each LD as follows [17]

$$\hat{s}_k = \underset{0\ldots 2^{\alpha_k}-1}{\operatorname{argmin}} \left| \mathbf{y} - \mathbf{c}_{|s_k} \right|^2, \tag{3}$$

where

$$\mathbf{c}_{|s_k} = \left[g_k^* \frac{1}{\sqrt{2^{\alpha_k}}} e^{j2\pi[(s_k+h) \bmod 2^{\alpha_k}]\frac{h}{2^{\alpha_k}}} \right]^T_{h=0..2^{\alpha_k}-1}. \tag{4}$$

The spectral efficiency for the LD, k, is equal to $\frac{\alpha_k}{2^{\alpha_k}}$, and hence, the average spectral efficiency for all LDs is expressed as

$$\eta = \frac{1}{K} \sum_{k=1}^{K} \frac{\alpha_k}{2^{\alpha_k}}. \tag{5}$$

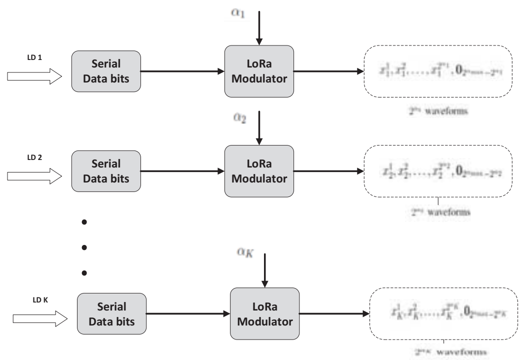

Fig. 1: LoRa system model.

Conventional LoRa networks assign a fixed SF to device such that higher SFs are assigned to devices that transmit over a longer distance. In addition, small-scale fading is not taken into consideration. The conventional LoRa architecture is named as the "static SF assignment scheme" in this paper.

In this paper, $(.)^H$ represents the Hermitian of a matrix, $(.)^T$ represents the transpose of a matrix, $|.|$ is the Euclidean norm of a vector, $\|.\|$ denotes the norm of a matrix, $\mathbf{0}_N$ denotes a vector with length N with zero entries and the binomial coefficient $\begin{pmatrix} . \\ . \end{pmatrix}$ is defined as $\begin{pmatrix} x \\ y \end{pmatrix} = \frac{x!}{(x-y)!y!}$

III. Spreading Factor Assignment

This section introduces the proposed dynamic SF assignment for LoRa networks. In particular, SFs are dynamically assigned during each channel realization based on the instantaneous channel quality in order to enhance the overall performance.

A. Problem Formulation

The SF assignment problem can be formulated as an optimization problem. The objective is to allocate dynamically the various orthogonal SFs among the LDs based on the instantaneous channel coefficients in order to minimize the average symbol error rate (SER). Hence, the main SF assignment problem can be formulated as

$$\begin{aligned} &\underset{\alpha_{k\,k=1..K}}{\text{minimize}} \quad \text{SER} \\ &\text{subject to} \\ &(6.a) : \alpha_k \in \Gamma,\ k = 1..K, \\ &(6.b) : \alpha_k \neq \alpha_p,\ \forall k \neq p. \end{aligned} \tag{6}$$

The formulated problem (6) is combinatorial and non-linear; and thus is a nonlinear integer problem (NLP).

B. SF Assignment Algorithm

The proposed low complexity SF assignment algorithm is given in this section. The aim of this algorithm is to assign higher SFs to the devices which suffer from poor channel gain and to assign lower SFs to the devices which exhibit better channel conditions. Each SF is assigned to only one device. The proposed algorithm takes the LoRa devices one by one in a sorting order according to their instantaneous channel gains $|g_k|^2$. At each iteration, it chooses the device with the maximum channel gain $|g_{k^*}|^2$ from the set of nonserved devices and assigns to it the lowest SFα_k^* from the set of unassigned SFs. Next, the used SF is discarded from the remaining set of SFs. This iterative procedure terminates once all devices are served. The details of the algorithm are given in **Algorithm 1**.

Algorithm 1 Dynamic SF Assignment Algorithm

1: $\alpha_k \leftarrow 0,\ \ k = 1 : K$, initialization
2: $\Omega \leftarrow \{1, 2, \ldots, K\}$
3: **for** $k = 1 : K$ **do**
4: $\quad k^* \leftarrow \underset{k\in\Omega}{\text{argmax}}\, |g_k|^2$, find device k^* with maximum channel gain
5: $\quad \alpha_k^* \leftarrow \min\ \Gamma$, assign device k^* minimum SF
6: $\quad \Gamma \leftarrow \Gamma \backslash \{\alpha_k^*\}$
7: $\quad \Omega \leftarrow \Omega \backslash \{k^*\}$
8: **end for**

C. Complexity Analysis

For the proposed dynamic SF assignment algorithm, the number of possible iterations is K in the worst case. At iteration k, this algorithm performs array search over two arrays with length $K - k + 1$ and $\bar{\Gamma} - k + 1$, where $\bar{\Gamma}$ is the number of SFs. Hence, the computational complexity of the proposed algorithm may be computed asymptotically as follows [18]

$$C^{dyn} = O\left(\sum_{k=1}^{K}(K - k + 1) + (\bar{\Gamma} - k + 1)\right) = O(\bar{\Gamma}K). \tag{7}$$

Thus, the dynamic SF assignment algorithm is characterized by a polynomial running time. The computational complexities of these algorithms are evaluated for different values of K in Table I considering $\bar{\Gamma} = 6$. Let C^{stat} denotes the computational complexity of the static SF assignment.

The proposed SF assignment algorithm requires instantaneous channel state information (CSI) feedback which involves an increase in energy consumption due to the additional consumed energy for channel estimation. Considering the minimum mean square error (MMSE) estimator and single-input single-output, this consumed power depends exclusively on the number of pilot signals and remains reduced compared to the total consumed power in the network system [19].

TABLE I: Computational Complexity of the proposed algorithm

Complexity order	C^{stat}	C^{dyn}
$K = 2$	1	12
$K = 3$	1	18
$K = 4$	1	24

IV. Numerical and Simulation Results

In this section, monte carlo simulations are used to evaluate the performance of the proposed scheme in terms of SER for LoRa networks. We consider a standard received power model which depends on the distance between devices, given by $\beta_k = \gamma^{\frac{k-1}{2}}$ where the received power coefficient $\gamma = 0.25$ The SER is evaluated while varying the signal-to-noise ratio (SNR), which is defined as the received power from a device to the noise power $SNR = \frac{\beta_k^2}{\sigma^2}$.

In Fig. 2, we investigate the performance of LoRa wireless networks by showing the symbol error rate versus the target SNR for different SFs when assuming only one LoRa device and $\gamma = 1$. Clearly, the symbol error rate decreases when increasing the SF. Therefore, in conventional LoRa system, we assign a higher SF to a device with a long distance within where the data can be received.

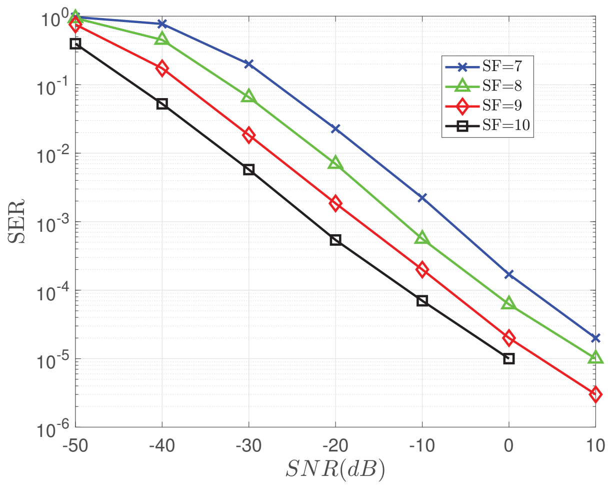

Fig. 2: SER of a single LoRa device under different SFs.

Fig. 3 plots the performance of the dynamic and static SF assignment schemes in terms of SER. It is clear that the dynamic algorithm significantly outperforms the conventional LoRa scheme, i.e. static SF assignment. The proposed dynamic scheme allows for a balanced SER between the devices in the network. The performance gap between the two schemes increases when the SNR increases or the number of served devices K in the network increases.

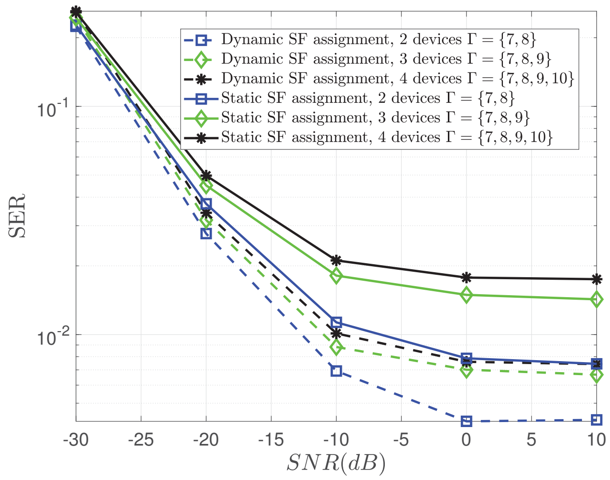

Fig. 3: Dynamic vs static SF assignment ($\gamma = 0.25$).

In Fig. 4, the SER of each device is shown for both the proposed dynamic scheme and the static scheme. It can be seen that device 1 saw the best enchantment after the dynamic scheme was adopted. The reason behind this is that previously in the static scheme, device 1 could only use a SF of 7. However, the dynamic scheme allows the device to use SF of 8 or 9 based on its channel conditions, which inherently improves its performance.

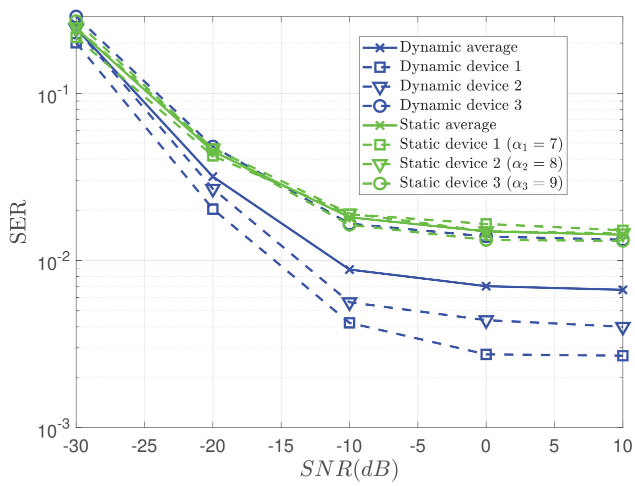

Fig. 4: SER per-device considering 3 LoRa devices ($\gamma = 0.25$).

In Fig. 5, the impact of the distance between devices on the system performance is shown. The figure clearly highlights the sensitivity of conventional LoRa schemes to distance between devices. In particular, the performance gap between the dynamic and the static SF schemes significantly increases when the LoRa devices are near to each other. The proposed dynamic solution takes into consideration the small-scale fading coefficient in the optimization problem in addition to the pathloss; thus allowing for an improved system performance.

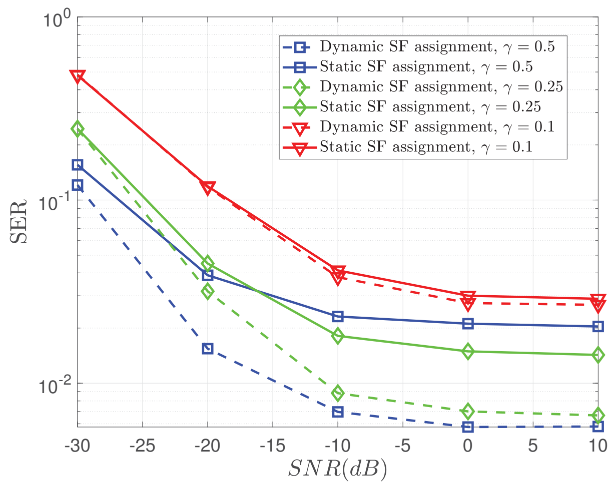

Fig. 5: Impact of the distance between devices ($K = 3, \Gamma = \{7, 8, 9\}$).

Fig. 6 illustrates the fairness level achieved by the proposed dynamic algorithm compared to the conventional static scheme. The used fairness metric is the well known Jain's fairness index [20] defined as $J(\mathrm{SER}) = \frac{\left(\sum_{k=1}^{K} \mathrm{SER}_k\right)^2}{K \sum_{k=1}^{K} \mathrm{SER}_k^2}$. Under the dynamic SF, the Jain index is close to 1 , indicating a higher fairness for the dynamic scheme compared to the static scheme. Indeed, the proposed algorithm provides higher fairness than the conventional LoRa scheme since it aims to balance the symbol error rate among LoRa devices by assigning higher SFs to the devices with bad channel conditions.

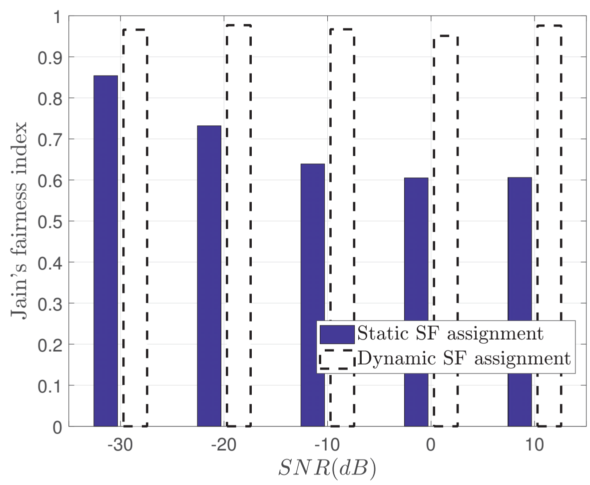

Fig. 6: Jain's fairness index ($K = 3, \Gamma = \{7, 8, 9\}, \gamma = 0.5$).

V. Conclusion

This paper investigates an alternative assignment scheme to the traditional LoRa SF assignment routine. In particular, this work proposes a reduced-complexity and efficient dynamic SF assignment algorithm based on the instantaneous channel coefficients. It was shown that the proposed scheme can significantly enhance the system performance of LoRa wireless compared to traditional SF assignment methods.

In order to enhance the spectral efficiency and the number of served devices in LoRa networks, future works will focus on developing novel transmission techniques based on index modulation and machine learning.

References

[1] A. Lavric and V. Popa, "Internet of things and LoRa low-power wide-area networks: a survey," *in Proc. of IEEE Int. Symp. Signals, Circuits Syst. (ISSCS)*, July 2017.

[2] Au. Ikpehai, B. Adebisi, K. M. Rabie, K. Anoh, R. E. Ande, M. Hammoudeh, H. Gacanin and U. M. Mbanaso, "Low-power wide area network technologies for Internet-of-things: A comparative review," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 2225-2240, Apr. 2019.

[3] C. Goursaud and J.-M. Gorce, "Dedicated networks for IoT : PHY / MAC state of the art and challenges," *EAI Endorsed Trans. Internet Things*, vol. 13, no. 1, pp. 1-11, 2015.

[4] M. Centenaro, L. Vangelista, A. Zanella, and M. Zorzi, "Long-range communications in unlicensed bands: the rising stars in the IoT and smart city scenarios," *IEEE Wireless Commun.*, vol. 23, no. 5, pp. 60-67, Oct. 2016.

[5] A. Augustin, J. Yi, T. Clausen and W. M. Townsley, "A study of LoRa: Long range & low power networks for the internet of things," *Sensors*, vol. 16, no. 9, pp. 1466, Sep. 2016.

[6] L. Vangelista, "Frequency shift chirp modulation: The LoRa modulation," *IEEE Signal Process. Lett.*, vol. 24, no. 12, pp. 1818-1821, Dec. 2017.

[7] M. Alsharef, A. M. Hamed, and R. K. Rao, 'Error rate performance of digital chirp communication system over fading channels," *in Proc. of World Congress Eng. Comput. Sci. (WCECS)*, Oct. 2015.

[8] O. Georgiou and U. Raza, "Low power wide area Network analysis: Can LoRa scale?," *IEEE Wireless Commun. Lett.*, vol. 6, no. 2, pp. 162-165, Apr. 2017.

[9] L. Amichi, M. Kaneko, N. El Rachkidy, A. Guitton, 'Spreading factor allocation strategy for LoRa networks under imperfect orthogonality," *in Proc. of IEEE Int. Conf. Commun. (ICC)*, May 2019.

[10] D. Zorbas, G. Z. Papadopoulosy, P. Mailley, N. Montavonty and C. Douligeris, 'Improving LoRa network capacity using multiple spreading factor configurations," *in Proc. of IEEE Int. Conf. Telecommu. (ICT)*, June 2018.

[11] G. Zhu, C. H. Liao, T. Sakdejayont, I. W. Lai, Y. Narusue and H. Morikawa, 'Improving the capacity of a mesh LoRa network by spreading-factor-based network clustering," *IEEE Access*, vol. 7, pp. 21584-21596, Feb. 2019.

[12] J.-T. Lim and Y. Han, "Spreading factor allocation for massive connectivity in LoRa systems," *IEEE Commun. Lett.*, vol. 22, no. 4, pp. 800-803, Apr. 2018.

[13] A. Farhad, D.-H. Kim, P. Sthapit and J.-Y. Pyun, 'Interference-aware spreading factor assignment scheme for the massive LoRaWAN network," *in Proc. of IEEE Int. Conf. Electron., Inf., Commun. (ICEIC)*, Jan. 2019.

[14] M. R. Winkler, 'Chirp signals for communications," *WESCON Convention Record Paper*, 1962.

[15] C. E. Cook, 'Linear FM signal formats for beacon and communication systems," IEEE Trans. Aerosp. Electron. Syst.," vol.10, no. 4, pp. 471-478. Jul. 1974.

[16] C. Gupta, 'T. Mumtaz, M. Zaman and A. Papandreou-Suppappola, 'Wideband chirp modulation for FH-CDMA wireless systems: Coherent and non-coherent receiver structures," *in Proc. IEEE Int. Conf. Commun. (ICC)*, May 2003.

[17] M. Leng and Y. C. Wu, 'Low-complexity maximum-likelihood estimator for clock synchronization of wireless sensor nodes under exponential delays," *IEEE Trans. Signal Process.*, vol. 59, no. 10, pp. 4860-4870, June 2011.

[18] R. Hamdi, E. Driouch and W. Ajib, "Energy Management in Hybrid Energy Large-Scale MIMO Systems," *IEEE Trans. Veh. Technol.*, vol. 66, no. 11, Nov. 2017.

[19] R. Kumar and J. Gurugubelli, "How Green the LTE Technology can be?," *in proc. of Int. Conf. on Wireless Commun., Veh. Technol., Inform. Theory and Aerosp. Electron. Syst. Techn.*, 2011.

[20] R. Jain, D. Chiu and W. Hawe, "A Quantitative Measure of Fairness and Discrimination for Resource Allocation in Shared Systems," *tech. rep., Digital Equipment Corporation*, DEC-TR-301, 1984.