

Evaluating the Performance of Multicast Resource Allocation Policies over LTE Systems

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Abstract—This paper addresses a multi-criteria decision method properly designed to effectively evaluate the most performing strategy for multicast content delivery in Long Term Evolution (LTE) and beyond systems. We compared the legacy conservative-based approach with other promising strategies in literature, i.e., opportunistic multicasting and subgroup-based policies tailored to exploit different cost functions, such as maximum throughput, proportional fairness and the multicast dissatisfaction index (MDI). We provide a comparison among above schemes in terms of aggregate data rate (ADR), fairness and spectral efficiency. We further design a multi-criteria decision making method, namely TOPSIS, to evaluate through a single mark the overall performance of considered strategies. The obtained results show that the MDI subgrouping strategy represents the most suitable approach for multicast content delivery as it provides the most promising trade-off between the fairness and the throughput achieved by the multicast members.

Index Terms—Networking and QoS, Traffic and performance monitoring, Multicast, LTE.

I. INTRODUCTION

The increase of the multimedia applications and number of enhanced devices (i.e., smartphone and tablet) poses tremendous challenges about the increasing of the radio resource utilization and services demand over mobile systems [1]. In this scenario, the usage of multicast services is expected to grow over current Long Term Evolution (LTE) and future 5G systems. In particular, multicasting will allow a large amount of users to be simultaneously served with the same service with relatively low latency and high quality of experience (QoE) [2][3]. As a result, the Third Generation Partnership Project (3GPP) poses the basic for the standardization of those kind of services with the name of Multimedia Broadcast Multicast Services (MBMS). This standard provides the guidelines in order to support multicast transmissions over LTE-based cellular systems and covers the implementation of different functionalities related to the point-to-multipoint protocol (e.g., service announcement, joining and leaving procedures, session setup and re-configuration).

However, although multicasting aims to offer several enhancements in multicast content delivery, several open issues are still under consideration over Orthogonal Frequency Division Multiple Access (OFDMA) systems, such as LTE. The most challenging issue is related to the multi-user diversity and to the different channel quality (and, consequently, supported data rates) experienced by the users in a multicast

group. Generally speaking, two different strategies for content delivery have been proposed in literature: (i) single-rate and (ii) multi-rate schemes. In the former case, a typical solution is represented by the *conventional multicast scheme* (CMS) where all the users within a multicast group are served based on the Modulation and Coding Scheme (MCS) of the user with worst channel condition. Even if this approach provides high network coverage, fairness [4] and high reliability, the potentials of the LTE systems are not fully exploited when the multicast group size increases drastically (i.e., users experience low data rate due to the presence of group members with poor channel capabilities).

To overcome these issues, the *opportunistic approach* has been proposed in literature. The aim of this approach is to serve, during each Transmission Time Interval (TTI), only the “best” portion of multicast members able to maximize the Quality of Service (QoS) of the served users. Therefore, it exploits the multi-user diversity in resource allocation, although it may limit the multicast gain, i.e., the number of users successfully served in each time slot. As a consequence, additional data coding (e.g., rateless codes) is required for avoiding the users to keep informed the transmitter of which portion of file is received. Although opportunistic approaches can achieve long-term fairness (which can be considered suitable in applications such as file delivery), they cannot achieve short-term fairness (since not all users are served within every time slot) that, on the contrary, is more important in streaming applications.

A promising scheme for multicast environments is represented by the *subgrouping* [5]. It divides the users into different subgroups based on perceived channel quality and serves all of them in the same TTI [5]. As a result, it is able to improve the session quality of the users by overcoming the typical issues related to the previous mentioned multicast approaches [6]. An example can be found in [7], where the authors proposed a novel subgroup-based strategy, namely the multicast dissatisfaction index (MDI), which is able to guarantee a satisfactory trade-off between the fairness and the data rates achieved by multicast group users.

Nevertheless, it is still really challenging to state, in an effective way, which is the most performing approach among those mentioned above [8]. As a consequence, to solve the aforementioned issues, in this paper we exploit a multi-criteria

decision making method, namely *Technique for Order of Preference by Similarity to Ideal Solution* (TOPSIS). TOPSIS is based on the concept that the chosen solution should have the shortest geometric distance from the ideal solution and the longest geometric distance from the negative solution. In particular, we use an extension of the TOPSIS method that exploits the fuzzy logic by evaluating the possible solutions with a similarity approach.

In this paper we propose an effective method to evaluate the most performing radio resource management (RRM) policies for MBMS [9] data delivery in LTE [10] and beyond networks. In particular, we investigate the performance of the different multicast RRM approaches in terms of (i) aggregate data rate (ADR), (ii) fairness, and (iii) spectral efficiency. Then, we use the obtained results as input for the TOPSIS method to provide an overall mark which clearly testifies which is the most performing RRM multicast scheme.

The remainder of the paper is summarized as follows. In Section II the considered system model and network configuration are presented. The considered multicast RRM strategies are described in Section III whereas the description of the TOPSIS method can be found in Section IV. The performance evaluation results are summarized in Section V whereas conclusive remarks are in Section VI.

II. SYSTEM MODEL

The reference scenario is represented by a single-cell multicast system where an LTE base station (i.e., the eNodeB) serves all the users (though a multicast transmission) within its coverage. Therefore, multicast services are managed with the enhanced Multimedia Broadcast Multicast Services (eMBMS), which is able to guarantee optimized transmissions of multicast and broadcast sessions (see Fig. 1).

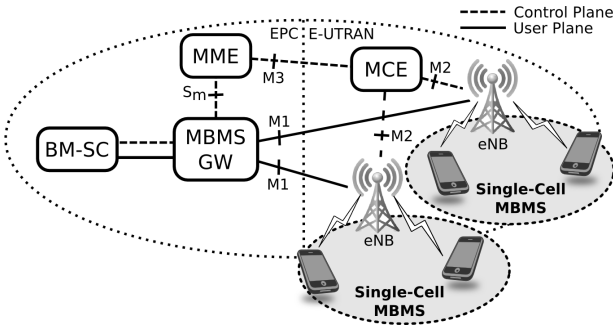


Fig. 1. eMBMS scenario.

The LTE downlink interface uses the OFDMA technique where the available radio spectrum is split into several Resource Blocks (RBs). The RB corresponds to the smallest time-frequency resource (12 sub-carriers) that can be allocated to a UE in LTE. The total number N of available RBs depends on the system bandwidth configuration and is managed by the packet scheduler, implemented at the eNodeB. In addition, the RRM exploits the Channel Quality Indicator (CQI) of multicast users to properly manage, on a *per-group* basis,

the transmission parameters and the N available RBs. We indicate with u_m the number of users with a CQI value $m = \{1, \dots, M\}$, where $\sum_{m=1}^M u_m = K$. Let b_m be the data rate obtained if one RB is transmitted with the MCS related to the CQI index m . The MCS (or MCSs) and the amount of assigned resources are decided by the eNodeB according to u_m values. We denote with $\mathbf{R} = \{r_1, \dots, r_M\}$ the RRM decision, with $\sum_{m=1}^M r_m = N$. If the generic item $r_m \in \mathbf{R}$ is greater than zero, then the base station enables the m -th MCS and r_m represents the amount of assigned RBs. According to $\mathbf{R}$, the data rate experienced by users with CQI equal to m is $d_m = \max(r_i b_i)$, with $i = 1, \dots, m$, i.e., each user is associated to the closest MCS enabled by the base station according to the experienced CQI.

III. MULTICAST RRM STRATEGIES

In this section we describe the different strategies addressed in this paper. In particular, in this work we use a typical single-rate strategy represented by the CMS approach, a multi-rate opportunistic multicast scheme (OMS), and several subgroup-based strategies.

A. Conservative Multicast Scheme

The *conservative multicast scheme* (CMS) [9] selects the MCS according to the worst channel conditions experienced in the multicast group, i.e., $r_{m^*} = N$, with $m^* = \min\{m | u_m > 0\}$. Therefore, we assume that m represents an indication of the maximum MCS level supported by the terminal in order to successfully decode the received signal with a Bit Error Rate (BER) smaller than a predefined target value. Although the CMS maximizes the user fairness as all multicast members are served with the same data rate, such a rate is drastically bounded by the user(s) located at the cell border which, on average, experience poor reception conditions [11].

B. Opportunistic Multicast Scheme

Being tailored to overcome the poor throughput performance of CMS, the *opportunistic multicast scheme* (OMS) has been proposed with the idea to dynamically change the portion of served multicast users [12]. With this aim, the OMS enables the MCS that maximizes the Aggregate Data Rate (ADR), i.e., the sum of bits conveyed to multicast destinations. As a consequence, the RRM decision relevant to OMS is $r_{m^*} = N$, with $m^* = \arg \max(b_m \sum_{i=m}^M u_i)$. Therefore, the goal of OMS is to exploit the multi-user diversity in order to serve as many users as possible with the highest possible data rate in the same TTI. Indeed, the remaining users will be served in the subsequent TTI. It is worth noting that OMS suffers in terms of reduced multicast gain, i.e., OMS is designed to serve only a portion of the multicast group and this drastically reduces the overall short-term fairness [11].

C. Subgroup-based Schemes

A promising approach proposed to overcome the limitations of both CMS and OMS approaches is the *subgrouping* [?]. It is based on the idea of dividing the multicast group members into

subgroups according to the experienced channel conditions, where each subgroup is characterized by a different MCS and, consequently, portion of served users and assigned RBs. This technique allows to serve *all* the multicast destinations while exploiting multi-user diversity. In addition, by taking advantage of scalable video coding (SVC) techniques, the subgrouping approach represents an effective solution for efficiently conveying high quality broadband multicast services, such as IPTV. Finally, a further goal of this approach is that the subgroup formation can be properly tailored to deal with different objective functions [7]. A first approach, namely the *Maximum Throughput (MT)*, is based on the following optimization problem:

$$\arg \max_{\mathbf{R}} \sum_{m=1}^M d_m u_m \quad (1)$$

$$s.t. u_m > 0, \forall m | u_m > 0 \quad (2a)$$

i.e., the MT strategy aims at maximizing the ADR while guaranteeing a basic service quality to all multicast users as highlighted in the constraint (2a).

The *Proportional Fairness (PF)* subgroup-based strategy is designed to take into account the intra-group fairness, i.e., to reduce the difference between the throughput experienced by multicast users by maximizing the sum of logarithmic data rate:

$$\arg \max_{\mathbf{R}} \sum_{m=1}^M \log(d_m) u_m \quad (3)$$

subject to (2a).

Finally, the *Minimum Dissatisfaction Index (MDI)* has been proposed in [7] to guarantee an increased throughput with respect to the PF policy without meaningfully affecting the fairness among the multicast members. The MDI is based on the maximization of a novel cost function:

$$\arg \min_{\mathbf{R}} \frac{1}{K} \sum_{m=1}^M \frac{b_m N - d_m}{b_m N} u_m \quad (4)$$

subject to (2a). According to (4), the MDI minimizes the difference between the maximum attainable data rate by a user with CQI m , i.e., $b_m N$, and the assigned data rate.

IV. MULTICRITERIA DECISION METHOD: TOPSIS

The schemes summarized in Sec. III offer different performance. For instance, the CMS offers high fairness but really low data rates, whereas the OMS basically has a dual behavior compared to CMS. Subgrouping approaches overcomes CMS and OMS, although it is not easy to understand in an effective way which is the most performing subgroup policy as all of them aim to offer a trade-off between throughput and fairness.

To solve this issue, this paper exploits an effective approach allowing to measure the overall performance of multicast RRM strategies through a single mark thus guaranteeing to highlight the policy with the best overall performance. This results is obtained by using a *Multicriteria Decision-Making*

(MCDM) problem. The method chosen to solve the selection problem is TOPSIS [13], one of the most used methods for MCDM problems. It is based on the idea that the chosen solution among different alternatives should have the shortest geometric distance from the positive ideal solution and the longest geometric distance from the negative ideal solution.

In this work we use an extension of TOPSIS provided by [14], where the final evaluation of the different solutions is made by using a similarity approach instead of closeness criteria. Finally, we use the fuzzy similarity method to calculate the distance between two fuzzy rating (instead of vertex method). The MCMD problem can be described as follows:

- (i) a set of K decision-makers called $E = D_1, D_2, \dots, D_K$;
- (ii) a set of m possible suppliers called $A = A_1, A_2, \dots, A_m$;
- (iii) a set of n criteria, $C = C_1, C_2, \dots, C_n$;
- (iv) a set of performance ratings called $X = x_{ij}, i = 1, 2, \dots, m, j = 1, 2, \dots, n$ described accurately in [14]

Assuming that a decision group has decision-maker and that all fuzzy ratings and weights are trapezoidal fuzzy numbers $\hat{x}_{ijk} = (a_{ijk}, b_{ijk}, c_{ijk}, d_{ijk}, e_{ijk})$ and $\hat{w} = (a_{ij1}, b_{ij2}, c_{ij3}, d_{ij4}, e_{ij5})$; $i = 1, 2, \dots, m, j = 1, 2, \dots, n$, respectively. Then, the aggregate fuzzy ratings can be expressed as:

$$\hat{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}, d_{ij}, e_{ij}), \quad (5)$$

In addition, the aggregate fuzzy weights of each criterion can be calculated as:

$$\hat{w}_j = (w_{j1}, w_{j2}, w_{j3}, w_{j4}, w_{j5}), \quad (6)$$

Therefore, the metrics-selection problem can be expressed in matrix form as:

$$\hat{X} = \begin{bmatrix} \hat{x}_{11} & \hat{x}_{12} & \dots & \hat{x}_{1n} \\ \hat{x}_{21} & \hat{x}_{22} & \dots & \hat{x}_{2n} \\ \vdots & \vdots & & \vdots \\ \hat{x}_{m1} & \hat{x}_{m2} & \dots & \hat{x}_{mn} \end{bmatrix} \quad (7)$$

$$\hat{W} = (w_1, w_2, w_3, w_4, w_5). \quad (8)$$

Since the set of criteria can be divided into *benefit* criteria and *cost* criteria, the normalized fuzzy decision matrix can be represented as:

$$\hat{R} = [\hat{r}_{ij}]_{m \times n} \quad (9)$$

where the term r_{ij} includes both the set of benefits and the cost criteria represented by B and C , respectively. The weighted normalized fuzzy decision matrix by considering the importance of each criterion can be summarized as follows:

$$\hat{V} = (\hat{v}_{ij})_{m \times n} \quad (10)$$

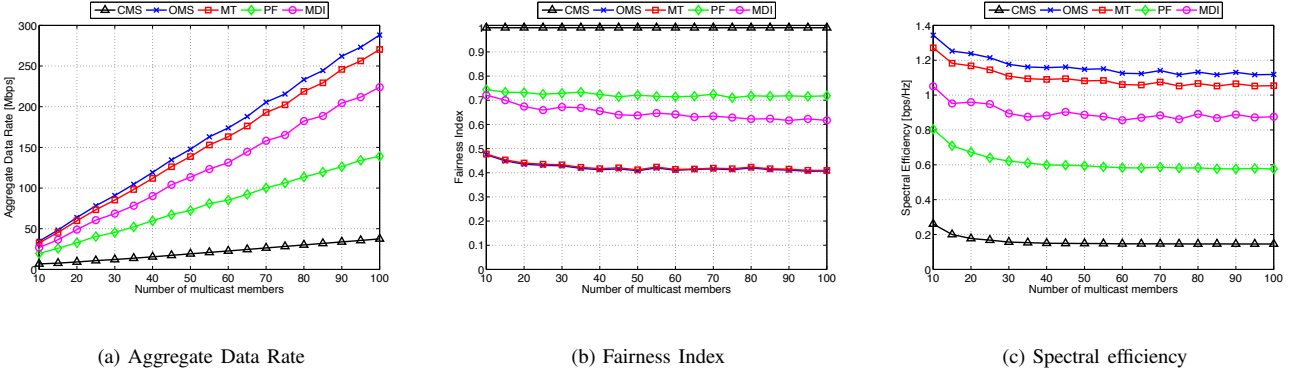


Fig. 2. Performance evaluation by varying the multicast group size in a scenario with $N = 15$ RBs.

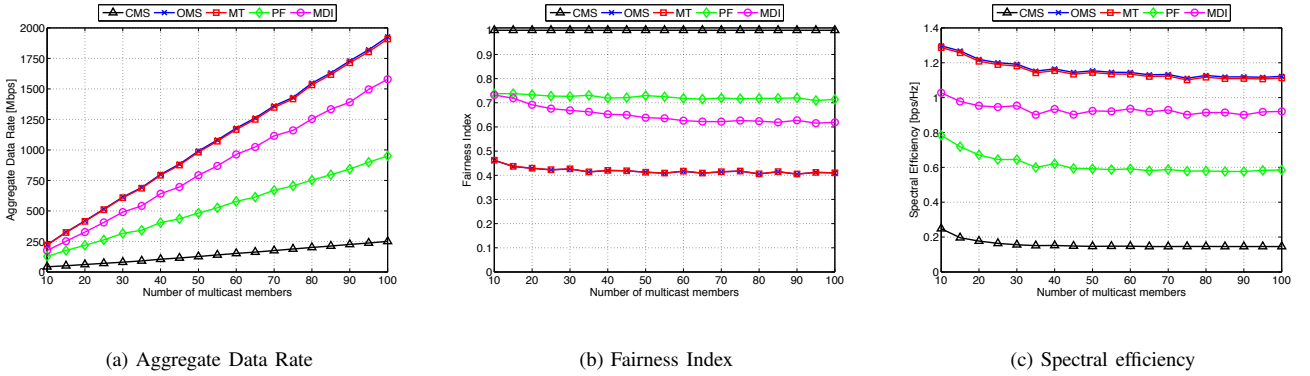


Fig. 3. Performance evaluation by varying the multicast group size in a scenario with $N = 100$ RBs.

where $\hat{v}_{ij} = \hat{r}_{ij}(\cdot)\hat{w}_j$. According to the aim of the TOPSIS algorithm, the fuzzy ideal solution (FPIS, A^+) and the fuzzy negative-ideal solution (FNIS, A^-) need to be defined as:

$$A^+ = (\hat{v}_1^+, \hat{v}_2^+, \dots, \hat{v}_n^+) \quad (11)$$

$$A^- = (\hat{v}_1^-, \hat{v}_2^-, \dots, \hat{v}_n^-) \quad (12)$$

Finally, we can calculate the fuzzy similarity matrix and, subsequently, simply compute the average of the similarities and use this as a similarity measure to achieve the final mark. This can be recast as follows:

$$S_i^+ = \frac{1}{n} \sum_{j=1}^n S_v(\hat{v}_{ij}, \hat{v}_j^+). \quad (13)$$

V. PERFORMANCE EVALUATION

A. Simulation Results

From the plethora of RRM policies mentioned above, it clearly emerges the need of simultaneously considering several target metrics to evaluate the performance of such policies. In this work, we consider three metrics: the ADR, the user

fairness (measured according to the well-known Jain's Fairness Index), and the spectral efficiency (i.e., the ratio between the data rate experienced by multicast members and the exploited channel bandwidth). In particular, we consider two different sets of available RBs that are represented by $N = 15$ and $N = 100$. The considered multicast group is composed by $K = 100$ subscribers uniformly distributed across the cell. The channel conditions for each UE are evaluated in terms of the SINR experienced over each subcarrier when path-loss, slow and fast fading affect the signal reception. The effective SINR, estimated according to the Exponential Effective SIR Mapping, is mapped onto the CQI level ensuring a Block Error Rate smaller than 10%. The results shown are obtained with a 95% confidence interval. The main simulation parameters are listed in Table I.

The ADR with $N = 15$ is shown in Fig. 2(a). We can observe that OMS and MT perform better compared to the other policies. In particular, CMS suffers in term of very low ADR although it reaches a fairness performance equal to 1. In fact, the results in terms of fairness (shown in Fig. 2(b)), outline that OMS and MT mainly focus on achieving high data rate instead of guaranteeing intra-user fairness. This behavior

TABLE I
MAIN SIMULATION PARAMETERS

Parameter	Value
Cell radius	500 m
Frame Structure	Type 2 (TDD)
TTI	1 ms
Cyclic prefix/Useful signal frame length	16.67 μ s / 66.67 μ s
Carrier Frequency	2 GHz
eNodeB Tx power	46 dBm
Noise power	-174 dBm/Hz
Path loss	128.1 + 37.6 log(d), d[km]
Shadowing standard deviation	10 dB (cell mode); 12 dB (D2D mode)
Sub-carrier spacing	15 kHz
BLER target	10%
# of Runs	500

can be further highlighted by results in Fig. 2(c), where the spectral efficiency for the considered strategies is shown. By focusing on the PF and MDI policies, we observe that these strategies try to obtain a throughput-fairness trade-off. With respect to OMS and MT, the PF and the MDI have lower ADR and spectral efficiency but higher fairness. Finally, the MDI is more performing than PF in terms of ADR and spectral efficiency but it achieves a lower fairness.

The trend for the ADR, fairness and spectral efficiency is almost the same also in case of $N = 100$ (see Fig. 3). The only differences are in terms of ADR and spectral efficiency: in particular, OMS and MT achieve the same performance. As a conclusion, it is clear that PF and MDI achieve a good level of fairness without strongly decreasing the user throughput. The OMS and MT, instead, are “rate” oriented whereas CMS is able to serve all the users with the side effect of very low data rates.

B. Topsis Evaluation

By analyzing the results in Fig. 2 and Fig. 3, we can observe the impossibility of having a RRM strategy that outperforms all other policies in all considered metrics; this makes very hard to define in an effective way which is the most performing multicast policy. To overcome this issue, in this work we use the TOPSIS decision making method. In fact, the problem of selecting the best policy among those investigated above can be approximated to a supplier selection problem in a supply chain (as typically addressed by the TOPSIS method). The MCMD problem can be described as follow:

- a set $\mathcal{D}$ of decision-makers represented by all the different multicast group size configurations taken into considerations in our simulation settings;
- a set $\mathcal{A}$ of A possible suppliers represented by the analyzed RRM approaches;
- a set $\mathcal{C}$ of C criteria, with which supplier performance are evaluated (i.e., ADR, fairness index and spectral efficiency);
- a set of performance ratings called $\mathcal{X}$ described accurately in [14].

The same general importance weight from the decision makers has been assigned to each criterion by following

TABLE II
DECISION MATRIX FROM THE DECISION MAKERS CONSIDERING 15 RBs

	ADR	FI	SE
CMS	VP	VG	F
OMS	VP	P	VG
MT	VP	VP	G
PF	VP	MG	VP
MDI	VP	MG	G

TABLE III
DECISION MATRIX FROM THE DECISION MAKERS CONSIDERING 100 RBs

	ADR	FI	SE
CMS	P	VG	F
OMS	VG	P	VG
MT	VG	VP	VG
PF	MP	MG	P
MDI	G	MG	G

TABLE IV
OBTAINED MARKS

CMS	OMS	MT	PF	MDI
0.4787	0.4657	0.4005	3219	0.6331

the linguistic variables expressed in positive fuzzy number proposed in [14]. This choice is aimed by the assumption that, in general, all the considered criteria have the same importance. Then, each decision maker expresses individually its own opinion about the criterion taken into account (i.e., ADR, fairness index and spectral efficiency). The TOPSIS algorithm has been executed for each considered multicast group size configuration (i.e., from 10 up to 100) and a final ranking is created in order to decide which is the best metrics that could be used.

The results shown in Table II and Table III¹ are useful to definitively select the most performing RRM strategy according to ADR, fairness and spectral efficiency parameters. In the evaluated scenarios with $N = 15$ RBs and $N = 100$ RBs, the MDI reaches the highest mark (see Table IV); this result highlights that the overall performance of MDI effectively overcomes the other considered policies. So doing, our exploited strategy is effectively able to indicate the RRM policy with the best results by taking into account several decision makers and performance metrics.

VI. CONCLUSIONS

In this paper we evaluated the performance of different multicast resource allocation policies in term of ADR, fairness and spectral efficiency. However, the obtained results shown the impossibility of having a RRM scheme that outperforms all other policies for all the considered metrics. To overcome this issue, we exploited an extension of the TOPSIS method based on fuzzy logic where the final evaluation is made by following a similarity approach. The achieved results after the TOPSIS process shown that the subgroup-based MDI strategy is the most suitable scheme for multicast service delivery in LTE

¹VP = Very Poor; P = Poor; MP = Medium Poor; F = Fair; MG = Medium Good; G = Good; VG = Very Good.

and beyond systems. In particular, MDI is able to provide high fairness without strongly affecting the throughput performance among the users belonging to the same multicast group.

REFERENCES

- [1] M. Fadda, V. Popescu, M. Murrone, P. Angueira, and J. Morgade, "On the Feasibility of Unlicensed Communications in the TV White Space: Field Measurements in the UHF Band," *International Journal of Digital Multimedia Broadcasting*, vol. 2015, Article ID 319387, 8 pages, 2015.
- [2] A. Tassi, C. Khirallah, D. Vukobratovic, F. Chiti, J.S. Thompson, and R. Fantacci, "Resource Allocation Strategies for Network-Coded Video Broadcasting Services over LTE-Advanced," *IEEE Transactions on Vehicular Technology*, Jul. 2014.
- [3] S.C. Spinella, G. Araniti, A. Iera, A. Molinaro, "Integration of Ad-hoc Networks with infrastructured systems for multicast services provisioning," *Ultra Modern Telecommunications & Workshops, 2009. ICUMT '09. International Conference on*, vol., no., pp.1.6, 12-14 Oct. 2009.
- [4] I. Bisio, M. Marchese, "The Concept of Fairness: Definition and Use in Bandwidth Allocation Applied to Satellite Environments," *IEEE Aerospace and Electronic Sys. Mag.*, vol. 29, no. 3, pp. 8-14, Mar. 2014.
- [5] G. Araniti, M. Condoluci, M. Cotronei, A. Iera, and A. Molinaro, "A Solution to the Multicast Subgroup Formation Problem in LTE Systems," *IEEE Wir. Com. Letters*, vol. 4, no.2, pp- 149-152, Jan. 2015.
- [6] G. Araniti, M. Condoluci, A. Iera, A. Molinaro, J. Cosmas, and M. Behjati, "A Low-Complexity Resource Allocation Algorithm for Multicast Service Delivery in OFDMA Networks," *IEEE Transactions on Broadcasting*, vol. 60, no. 2, pp. 358-369, Jun. 2014.
- [7] G. Araniti, M. Condoluci, L. Militano, and A. Iera, "Adaptive Resource Allocation to Multicast Services in LTE Systems," *IEEE Transactions on Broadcasting*, vol. 59, no. 4, pp. 658-664, Dec. 2013.
- [8] A. Tassi, I. Chatzigeorgiou, and D. Vukobratovic, "Resource Allocation Frameworks for Network-coded Layered Multimedia Multicast Services," *IEEE Journal on Selected Areas in Communications*, vol.33, no.2, pp. 141-155, March 2015.
- [9] 3GPP, TS 36.440, "General aspects and principles for interfaces supporting Multimedia Broadcast Multicast Service (MBMS) within E-UTRAN," Rel. 11, September 2012.
- [10] 3GPP, TS 36.300, "Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN)," Rel. 11, September 2012.
- [11] A. Richard, A. Dadlani, and K. Kim, "Multicast scheduling and resource allocation algorithms for OFDMA-based systems: A survey," *IEEE Comm. Surveys and Tutorials*, vol. 15, no. 1, pp. 240-254, 2013.
- [12] T. P. Low, M. O. Pun, Y. W. P. Hong, and C. C. J. Kuo, "Optimized opportunistic multicast scheduling (OMS) over wireless cellular networks," *IEEE Transactions on Wireless Communications*, vol. 9, no. 2, pp. 791-801, Sep. 2009.
- [13] H. Ching-Lai, L. Young-Jou, L. Ting-Yun, "A New Approach for Multiple Objective Decision Making," *Computers & Operations Research*, vol. 20, no. 8, pp. 889-899, Oct. 1993.
- [14] P. Luukka, "Fuzzy Similarity in Multicriteria Decision-Making Problem Applied to Supplier Evaluation and Selection in Supply Chain Management," *Advances in Artificial Intelligence*, vol. 2011, no. 6, Jan. 2011.