Radio-Aware Subgroups Formation for Multicast Traffic Delivery in WiMAX Networks

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Abstract—This paper focuses on the design of radio resource management policies for multicast service delivery in WiMAX networks. With the purpose of finding an alternative solution to the conventional multicast scheme that is conservative towards resource utilization, we propose to use a subgroup-based link adaptation technique that dynamically chooses the modulation and coding schemes based on the perceived channel conditions in each subgroup of multicast receivers. The main idea is to split the multicast destinations into different subgroups depending on the perceived channel quality, and to apply subgroup-based adaptive modulation and coding for a more efficient spectrum exploitation. The performance of different solutions for the subgroups formation will be analyzed and their effectiveness evaluated through simulations to show how the network can take advantage from the proposed subgrouping approach.

Index Terms—WiMAX, Multicast, Adaptive Modulation and Coding, Scheduling

I. INTRODUCTION

WiMAX networks, specified in the IEEE 802.16 standard [1], represent an effective solution for broadband wireless provisioning, because of their ability to provide large volume of contents to a high number of users distributed over large areas in a cost-effective manner.

The centralized architecture of WiMAX networks offers a natural support for multicast service delivery. The Base Station (BS) schedules transmission opportunities to the Subscriber Stations (SSs) belonging to the same multicast group in its coverage area.

Providing a satisfactory service to all multicast users is a challenging task, not only due to the high bandwidth demands and stringent delay constraints of many multicast applications, but also because WiMAX networks operate in a challenging environment due to the space- and time-varying nature of the radio channel. Adaptive modulation and coding (AMC) techniques can be used to mitigate the negative effects caused by impairments on the wireless channel. They permit to dynamically choose the modulation and coding scheme (MCS) that is suitable to the current radio link status.

When providing multicast services in a WiMAX environment, the main problem is that the SSs belonging to the same multicast group may perceive different channel conditions. While the users with a good channel could receive multicast traffic at a high data rate, the group members with poor channel conditions need more robust MCSs, thus becoming the bottleneck of the multicast group and causing conservative resource utilization.

With the purpose of providing multicast services to all the group members, while avoiding that users affected by adverse channel conditions negatively impact the performance of the overall group, we propose a subgroup-based resource allocation scheme. The main idea is to distribute the multicast receivers into different subgroups depending on the measured channel quality, and to deliver multicast traffic to each subgroup by using the proper MCS. The main tasks of the proposed resource allocation algorithm implemented at the WiMAX BS are: (i) determining the optimal number of subgroups to activate in its cell, and distributing the multicast receivers under coverage among the activated subgroup; and (ii) allocating the radio resources to each subgroup every WiMAX frame.

The main contribution of this paper can be summarized as follows: (i) we propose to cluster SSs with similar channel quality in the same multicast subgroup of a WiMAX cell; (ii) we propose different cost functions for subgroup formation to trade off fairness and throughput requirements; (iii) we show by simulations that subgrouping offers significant improvements in the system performance compared to the conventional approach of creating one single multicast group in the cell. The proposed technique can be considered as a general-purpose technique for the distribution of multicast services; it is also suited to support video streams with multi-layer coding [2] where, frame-by-frame, the base-layer can be delivered to all the multicast receivers in the cell, while the enhancement layers are only delivered to SSs in the subgroups with adequate channel quality.

The remainder of this paper is organized as follows. In section II, background and motivations of our work are presented. Section III describes the proposed subgroup-based resource allocation scheme with the different techniques for subgroup formation. Simulation results are presented in section IV, and concluding remarks are reported in the last section.

II. BACKGROUND AND MOTIVATIONS

The WiMAX technology has been specified in the IEEE 802.16 standard [1]. The network is centrally managed by the BS that offers connection-oriented services to SSs under its radio coverage. WiMAX networks can operate either in TDD (Time Division Duplexing) or FDD (Frequency Division Duplexing) mode. The results reported in this paper refer to
the TDD case, but the principles of the proposal are valid regardless of the duplexing method.

At the physical (PHY) layer, WiMAX uses the Orthogonal Frequency-Division Multiplexing (OFDM) scheme. It also exploits adaptive modulation and coding in order to dynamically choose the best MCS for a given channel quality. AMC can noticeably improve the system performance, and this is very meaningful in providing group-oriented services.

With regards to the capability of WiMAX networks to support multicast traffic, the standard includes options to send data on multicast connections that are identified by a multicast connection identifier (MCID).

Although the literature on resource allocation in WiMAX networks mainly focused on unicast traffic (a survey can be found in [3]), multicasting over WiMAX represents a timely research field. In [4] the authors present an overview of multicast and broadcast multimedia services concepts and design principles in WiMAX covering both air link aspects and end-to-end network architecture. In [5] a multicast and broadcast service (MBS) architecture is designed for mobile WiMAX. Analogously to the multicast and broadcast architecture designed for cellular systems, it includes a new functional entity that supports the multicast functionality, namely the MBS controller (MBSC) that serves as an entry point for contents providers.

In [6], the authors propose a cooperative transmission model for efficiently supporting multimedia applications in WiMAX. It is composed of two phases: first the BS multicasts data at a high rate and, later, users in good channel conditions help in relaying the received data to the remaining users. Multicasting of video streaming in WiMAX networks has been analyzed in [7] and [8]. In [7] the authors consider the problem of providing real time video applications by taking into account that channel conditions can vary considerably across users. The use of layer encoded video ensures that all users have access to the base layer, while enhancement layers are supplied only to users with favorable channel conditions. The problem of maximizing the video quality and minimizing the energy consumption for mobile receivers with limited resources is considered in [8]. In particular, they consider broadcasting multiple scalable video streams composed of multiple layers to mobile receivers, and formulate the problem of selecting the best set of layers from the scalable video streams in order to maximize the quality for mobile receivers.

An interesting approach that aims at enhancing the radio channel utilization in multicast environments is subgrouping that puts multicast group members with similar measured channel quality into the same subgroup. Both system capacity and session quality can improve with subgrouping, since the negative effects produced by edge-cell users is reduced. Applications of this approach can be found in [9] and [10] for OFDMA and High Speed Downlink Packet Access (HSDPA) networks, respectively. To the best of our knowledge, a similar policy has not been applied in WiMAX networks yet. Although the cited studies demonstrate the effectiveness of subgrouping in improving the multicast traffic delivery performance, both the proposed solutions create the subgroups by taking into account only the system throughput maximization. We propose to use subgrouping for multicast traffic support in WiMAX networks and evaluate the effectiveness of this approach with different techniques for subgroup formation, which also take into account fairness in the radio resource assignment.

III. SUBGROUP-BASED RESOURCE ALLOCATION IN WiMAX NETWORKS

Let us consider the general case where the multicast group (MG) is composed by \( K \) SSs. Let \( MCS_c \) be a generic modulation and coding scheme, with \( c \) that varies from 1 to a maximum level \( C; C = 7 \) in the WiMAX system (refer to Table I). For a given \( MCS_c \), the attainable data rate is function of the number of assigned OFDM symbols. Such a rate can be defined as \( d_c = rb_c \), being \( b_c \) the data rate achieved when 1 OFDM symbol is transmitted with \( MCS_c \) and \( r \) the number of OFDM symbols assigned by the BS to the SS. The \( r \) value can vary from 1 to \( R \), where \( R \) depends on the system bandwidth configuration [1]. It is worth noting that a generic SS supporting an MCS equal to \( MCS_c \) can successfully demodulate the received signal only if it served with a MCS equal to \( MCS_j \) with \( j \leq c \).

The BS is in charge of identifying the most appropriate subgroup configuration (i.e., the number of subgroups and their related MCSs), assigning users to subgroups and allocating resources to each activated subgroup accordingly. The proposed radio resource management (RRM) policy implemented at the BS is composed of three main phases that will be described in the following.

A. Channel monitoring

Channel awareness is considered mandatory to make the subgrouping and resource allocation algorithms effectively work. A channel state monitoring function makes the BS aware of the quality of links toward each SS under its radio coverage. We assume that all SSs perform Radio Signal Strength Intensity (RSSI) and Carrier to Interference and Noise Ratio (CINR) measurements, update estimates of the RSSI’s and CINR’s mean and standard deviation values, and report them back to the BS. Signaling messages used for this purpose can be the textitBandwidth Request and CINR report messages specified in IEEE 802.16 [1].

Two assumptions hold in this paper: (i) the link quality remains constant on a per-frame basis; so channel measurement reports received at each frame beginning are valid for the entire frame; this is equivalent to modeling a block-fading channel, which is a reasonable assumption for the slowly varying radio links of the fixed WiMAX scenario; (ii) perfect channel state information is available at the BS; i.e., channel measurement reports are received over an error-free feedback channel. This last assumption is commonly used in fixed wireless environments as the one under analysis.

In order to determine the MCS suitable to each BS to SS transmission, the monitored channel quality is compared against the allowed values of Signal-to-Noise Ratio (SNR) and
minimum input level sensitivity ($R_{SS}$) for each burst profile at a given bit error rate (BER). $R_{SS}$ values, reported in Table I, have been calculated according to the specifications in [1], for a BER measured after the FEC block lower than $10^{-6}$ and for standard message and test conditions, as in the following:

$$R_{SS} = -102 + SNR_{RX} + 10 \cdot \log \left( F_s \cdot \frac{N_{\text{used}}}{N_{\text{FFT}}} \cdot \frac{N_{\text{subchannels}}}{16} \right)$$

(1)

where:

- $SNR_{RX}$ is the receiver SNR, reported in Table I;
- $F_s$ is the sampling frequency [MHz] calculated as $n = \text{floor}(n \cdot BW/8000)$, where $n$ is a sampling factor and BW is the nominal channel bandwidth. We assume 7 MHz channel and $n = 8/7$, as suggested in [1];
- $N_{\text{used}}$ is the number of used subcarriers;
- $N_{\text{FFT}}$ is the smallest power of two greater than $N_{\text{used}}$;
- $N_{\text{subchannels}}$ is the number of allocated subchannels (default 16 if no subchannelization is used).

When the received signal level is below the receiver sensitivity for a given profile and target BER, a more robust transport mode should be chosen, if available. A channel can be used for transmission as long as there is a burst profile which is capable to cope with its current status. Otherwise, if the signal level is below the receiver sensitivity even for the most robust burst profile (BPSK modulation with 1/2 coding rate), then the channel is considered too poor for sending packets.

In the channel monitoring phase the BS collects the channel quality information from each SS belonging to the multicast group. The MG can be expressed through the multicast user set $K$, where $K = |K|$ represents the MG size, i.e., the number of SSs in the group. The MCS supported by the generic SS is denoted with $MCS^k$, with $k = 1, 2, \ldots, |K|$.

The BS saves the channel state information received by all the multicast members in the vector $U = \{u_1, u_2, \ldots, u_C\}$, where the generic item $u_c$ represents the number of SSs supporting a MCS level equal to $MCS_c$. As a consequence $\sum_{c=1}^C u_c = K$. Vector $U$ keeps the BS aware of the maximum MCS supported by each SS and is the input parameter for the subgroups creation phase.

### B. Subgroup creation

In the subgroup creation phase the BS applies its RRM policy by starting from the knowledge of the $U$ vector. The resource allocation procedure organizes the multicast receiving SSs into subgroups by taking into account the collected CINR reports and, then, selects the appropriate number of OFDM symbols and transmission parameters for each enabled subgroup. The assumption that holds is that all the SSs experiencing the same channel quality will be associated to the same subgroup, while a subgroup could serve SSs with different associated MCS. Under this assumption, the possible number of different subgroups, i.e., $S$, varies from 1 to $C$.

The set of users belonging to the $s$-th subgroup (with $s = 1, 2, \ldots, S$) is denoted with $K_s \subseteq K$ and $K_s = |K_s|$ represents the number of SSs served by such a subgroup. The $s$-th subgroup is served according to the minimum MCS among those supported by users belonging to the subgroup, i.e., according to $\min_{k \in K_s} MCS^k$. This condition guarantees that each SS within the subgroup can successfully support the content delivery. The output of this phase, i.e., the subgroup configuration, is selected by the RRM in order to optimize a given cost function $P$. Such a configuration is denoted by the subgroup vector $R = \{r_1, r_2, \ldots, r_C\}$, where $0 \leq r_c \leq R$ and $\sum_{c=1}^C r_c = R$. If $r_c \neq 0$ the subgroup with an MCS equal to $MCS_{c}$ is enabled and $r_c$ is the amount of OFDM symbols assigned to the subgroup. The number of enabled subgroups is given by the number of items in $R$ greater than zero.

### C. Radio resource allocation

When subgroups have been created, the multicast service is finally provided. Depending on $R$, the generic SS supporting a modulation and coding scheme equal to $MCS_c$ will be served with a data rate:

$$a^R_c = \text{max } \{r_i b_i \text{ }, \text{ } i = 1, 2, \ldots, c\}$$

(2)

indicating that the SS is served with the MCS closest to those allowed by the perceived channel condition. According to (2), the BS constructs the data rate vector $D^R$ that stores the data rate per MCS level.

### D. Radio-Aware Subgrouping Techniques

In the following, we present different policies for subgroup formation tailored to WiMAX networks. In particular, we first describe the traditional technique and then the two proposed subgrouping algorithms, namely Maximum Throughput (MT) and Proportional Fairness (PF). They differ in the definition of the cost function: while MT aims at maximizing the network throughput, PF tries to fairly distribute the available resources among the multicast receivers.

#### Conventional Multicast Scheme (CMS): It is a particular case of subgrouping that applies a conservative approach for reliable multicast content delivery [11]. Only one single group is activated ($S = 1$) and all the available $R$ OFDM symbols are transmitted with the minimum MCS among those supported by all the SSs, i.e., according to $\min_{k \in K} MCS^k$. As all SSs are served, the network coverage is maximized.

### Conventional Multicast Scheme (CMS)

(Continued...)
Although CMS represents the fairest solution (all multicast destinations are served with the same data rate), it introduces severe inefficiencies especially when the number of users with poor channel conditions is small.

**Maximum Throughput (MT):** The throughput degradation introduced by the CMS approach can be overcome by implementing the MT [9] resource allocation for subgroup creation. The main objective of MT is the maximization of the Aggregate Data Rate (ADR), defined as the sum of the receiving data rate of all the multicast SSs. The optimization of the cost function $P$ tailored for a MT approach in WiMAX networks is defined as follows:

$$MT = \arg \max_{R \in \mathbb{R}} \left\{ \sum_{c=1}^{C} r_c u_c \right\} = \arg \max_{R \in \mathbb{R}} \left\{ \mathbf{d^R} \cdot \mathbf{u^R} \right\}$$  \hspace{1cm} (3)$$

subject to:

$$\sum_{c=1}^{C} r_c = R$$  \hspace{1cm} (4)

where $\mathbb{R}$ represents the search space for the RRM optimization problem. Constraint (4) guarantees that the whole set of OFDM symbols is assigned by the BS.

The MT approach cannot guarantee full network coverage. Indeed, data rate maximization can be achieved by avoiding transmitting data to the subset of SSs which excessively bound the data rate of the group (cell-edge SSs). These SSs are considered in “outage” condition and so they are not scheduled by the BS.

A further constraint, defined as:

$$d_c^R > 0 \quad \forall c \mid u_c > 0$$  \hspace{1cm} (5)

shall be introduced in order to guarantee a total coverage. This constraint assures, in case of layer-encoded video for example, that the base layer is conveyed to all group members, while enhancement layers are provided only to a subset of users that can dynamically change frame by frame. We will refer to this policy as Maximum Throughput with Total Coverage (MTTC).

**Proportional Fairness (PF):** Although MT guarantees the maximum achievable throughput for a given configuration $\mathbf{U}$, other parameters such as fairness need to be evaluated for practical systems implementation. The PF scheduling represents a suitable solution for subgroup creation aiming at improving fairness among the users altogether with increasing the system throughput. Firstly, the PF was defined in [12] in [13] it was demonstrated that a proportional fairness allocation problem can be represented as an optimization problem for maximizing the sum of logarithmic data rates. The cost function $P$ based on the PF approach tailored to WiMAX networks is defined as follows:

$$PF = \arg \max_{R \in \mathbb{R}} \left\{ \sum_{c=1}^{C} \log(d_c^R) u_c \right\}$$  \hspace{1cm} (6)

subject to constraints (4) and (5).

The PF policy also guarantees the system capacity maximization. Indeed, in a given subgroup configuration where one or more SSs are not scheduled (then their data rate is equal to zero) the cost function $P$ will approach $-\infty$. In this way, such a configuration will be never selected by the RRM, since subgroup creation is aimed at maximizing the sum of logarithmic rates. Consequently, it is always guaranteed that the PF algorithm will select a subgroup configuration $\mathbf{R}$ where each SS receives a data rate greater than zero.

**Remark 1.** Since the cardinality of the set $\mathbb{R}$ is bounded, the optimization problems defined in (3) and (6) admit at least one solution. In case of multiple solutions a reasonable choice can be any configuration maximizing the radio channel exploitation.

**Remark 2.** The computational cost of both (3) and (6) problems does not depend on the multicast group size, but only on the number of MCS levels (i.e., $C$) and the maximum number of OFDM symbols assigned for the multicast service (i.e., $R$). The number of possible configurations to be assumed by $\mathbf{R}$ when $R$ OFDM symbols are split among $C$ subgroups (worst case) is bounded by $O(R^C)$.

**IV. PERFORMANCE ANALYSIS**

The performance evaluation of the three subgrouping and resource allocation algorithms under investigation has been run in Matlab. Each simulation run has been repeated several times to get 95% confidence intervals in the presented results.

The reference WiMAX network topology includes a BS in the centre of a 1000m x 1000m grid and 50 SSs placed at different distances from the BS. We consider the following four scenarios illustrated in Figure 1:

- **Uniform Distribution**: SSs are uniformly distributed across the grid;
- **Edge Hot Spot**: SSs are located near the cell borders;
- **Central Hot Spot**: SSs are close to the BS;
- **Sparse Hot Spots**: SSs are equally distributed between a central and an edge hot-spot.

The analyzed scenarios differ in the user distribution while the number of SSs is invariant.

The channel characteristics have been simulated through the Stanford University Interim (SUI-6) channel model defined in [14] for fixed broadband wireless applications in terrain Type A, that is hilly terrain with moderate-to-heavy tree densities. The model accounts for both macroscopic channel effects, such as path loss (PL) and shadowing (s) according to Eq. 7, and microscopic effects, such as multipath fading, which is modelled as a tapped delay line with 3 taps with non uniform delays and maximum Doppler frequency (propagation model specifications are reported in Table II).

$$PL = 20 \log_{10} \left( \frac{4 \pi d_0}{\lambda} \right) + 10 \gamma \log_{10} \left( \frac{d}{d_0} \right) + X_f + X_h + s$$  \hspace{1cm} (7)

where $d$ is the distance between SS and BS antennas [m]; $d_0$=100m; $s$ is a log normally distributed variable that accounts for the shadow fading. The path loss exponent is $\gamma = (a - b \cdot h_b + c/h_b)$, the constant values used for $a$, $b$ and $c$ depend on the terrain type, and $h_b$ is the BS antenna height above ground. Correction factors $X_f$ and $X_h$ respectively account of
an operating frequency outside 2.5 GHz and the SS antenna height above ground \( (h_r) \).

**TABLE II**

<table>
<thead>
<tr>
<th>Propagation model specifications</th>
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<tr>
<td>Channel model</td>
</tr>
<tr>
<td>BS (omn.) antenna height ( (h_b) )</td>
</tr>
<tr>
<td>SS antenna height ( (h_r) )</td>
</tr>
<tr>
<td>BS power</td>
</tr>
<tr>
<td>Frequency band</td>
</tr>
<tr>
<td>a, b, c constants</td>
</tr>
<tr>
<td>Correction factors</td>
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<tr>
<td>Shadowing</td>
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<tr>
<td>Multipath fading</td>
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</table>

The downlink subframe is assigned a maximum number of 150 OFDM symbols for each TDD frame [1] to account for the presence of downlink traffic.

Performance parameters that are evaluated for assessing the behavior of the analyzed subgrouping algorithms are:

- **Aggregate Data Rate (ADR):** represents the system throughput, i.e., the sum of throughput experienced by users and is evaluated as follows:

  \[
  ADR = \sum_{c=1}^{C} d_c u_c \quad (8)
  \]

- **Channel Data Rate (CDR):** accounts for the total amount of user data transmitted by the BS over the air interface.

- **Jain’s Fairness Index (JFI):** evaluates the fairness in the goodput distribution among users in the same MG. It is calculated according to [15] as in Eq. 9. JFI takes values in the range \( \in [1/K, 1] \) and is equal to 1 in the case of perfect fairness.

  \[
  JFI = \frac{\left( \sum_{c=1}^{C} d_c u_c \right)^2}{K \sum_{c=1}^{C} (d_c)^2 u_c} \quad (9)
  \]

- **Network Coverage:** indicates the MG percentage that is actually served during the multicast session. For a given data rate \( x \), coverage is defined as the percentage of UEs served with a data rate equal or lower than \( x \).

Figures 2(a) and 2(b) show, respectively, the achieved performance in terms of ADR and CDR in the four analyzed scenarios. In all scenarios, the MT algorithm provides the best performance while the limitations of the CMS algorithm are clearly visible. The MTTC policy guarantees performance close to MT whereas the PF algorithm represents a compromise between CMS and MT/MTTC. It shows considerably higher performance than CMS even if it is not able to achieve the performance assured by MT/MTTC.

Figure 2(c) shows that, in terms of JFI, the relationship between MT, MTTC and PF is overturned with respect to ADR and CDR. In fact, in this case, PF algorithm represents a compromise between CMS (that provides the maximum fairness because all users obtain exactly the same performance) and MT/MTTC policies. It is worth noting that MTTC provides almost the same JFI performance compared to MT algorithm.

Figure 3 shows the network coverage in the analyzed scenarios. The CMS, MTTC and PF algorithms provide full network coverage (all users are served), while MT reaches, in the most favorable scenario (Central Hot Spot in Fig. 3(c)), a network coverage of approximately 80%. Looking at the extremities of the three curves in each figure, in accordance to what is shown in Fig. 2(a), the CMS algorithm is able to serve all users with a very low data rate while MT guarantees the best performance at the expense of a reduced network coverage. MTTC has the benefit to serve all users (as CMS and PF) with a very small throughput cutback with respect to MT. Finally, PF demonstrates again to be a compromise between MT/MTTC and CMS.
V. Conclusions

In this paper we have analyzed the problem of efficiently delivering multicast services in WiMAX networks. We have proposed to use subgroup-based AMC as an alternative to the CMS approach, and we have analyzed the performance of different subgroup formation solutions. The analysis of achieved results has clearly shown that (i) CMS is not an effective solution because of its severely limited performance caused by a conservative resource utilization, (ii) subgrouping-based AMC algorithms provide significant performance improvement, and (iii) there is a tradeoff between fairness and network throughput when implementing PF and MT approaches. Network operator has the chance either to fairly distribute the network resources among the multicast receivers by implementing the PF policy, or to maximize the network throughput through the MT algorithm. Among the techniques that maximize throughput, MTTC approach is preferable because it assures full coverage at the expense of a negligible network throughput reduction.

Further techniques aiming at reducing the computational cost of subgroup creation are currently under investigation and will be the focus of our future work.

References