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Multicast vs multiple unicast scheduling in high-speed cellular networks

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Abstract— Packet scheduling is one of the key features in data-oriented radio interfaces of cellular networks like HSDPA (High Speed Downlink Packet Access). It has been primarily designed for unicast applications. Nevertheless, unicast may not optimise the resource usage when the same content has to be transmitted to several users in the same cell. In this paper, we compare the performance of multicast and unicast scheduling considering both a theoretical generic system and an HSDPA system. We prove the benefit of deploying multicast which is found to have merits when the average channel quality is good enough. Results show that the better the average channel quality is, the more users are allowed to receive the service simultaneously.

I. INTRODUCTION

Packet scheduling is the functionality that distributes radio resources between users. It tries to serve them fairly while maximising the system throughput. Intensive research has been conducted on the performance of unicast schedulers in cellular networks, especially in the context of HSDPA (e.g. [4], [5], [7]). During a service session, users may experience different channel conditions from a slot to another. The packet scheduler uses the reported channel qualities and chooses at each Transmission Time Interval (TTI) the user to serve with the suitable modulation and coding scheme. Here, we consider an opportunistic scheduler which serves the user having the best Signal to Noise Ratio (SNR).

In some multimedia applications (e.g. video streaming), it may be interesting to transmit the same content to several users within the same cell. The standard way to manage these applications is to duplicate transmission to the different User Equipments (UEs). This may however considerably waste radio resource as only one user is served at each time slot. In this paper, such an approach is called multiple unicast. An interesting alternative is to multicast data on high capacity channels like the High Speed-Downlink Shared Channel (HS-DSCH) and deliver the same content to several users at the same time. Though not defined in the HSDPA standard, multicast may be implemented on the HS-DSCH by use of group identifier; the protocol modification details are not in the scope of this work. In order to avoid packets loss, the multicast scheduler must consider the worst case; i.e. adapt the transmission bitrate to the mobile that has the lowest SNR. Hence, the gain of using such a conservative multicast scheduling instead of the multiple unicast scheme of the standard systems is not easily predictable. Our objective is

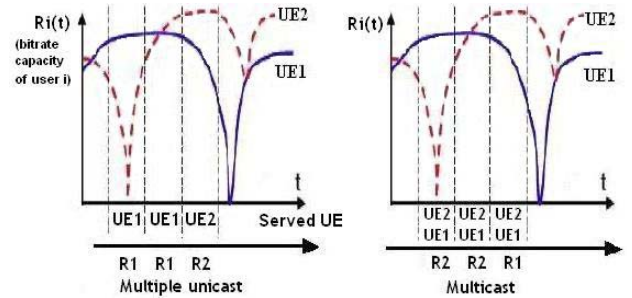


Fig. 1. Multiple unicast vs multicast scheduling considering 2 UEs

then to quantify the gain of using multicast instead of the conventional multiple unicast. More precisely, we compare the performance of a discontinuous service using the maximum bitrate capacity to a continuous service using the lowest supported bitrate (Fig. 1). The study can be applied to any type of service (e.g. file transfer, video streaming, etc.).

It is noteworthy that other multicast schedulers can be used such as MPF and IPF [9]. However, although these algorithms allow higher multicast bitrates, packet losses are frequent and resulting retransmissions may decrease the system performance. Forward Error Correction (FEC) has to be applied to scalable video coding to properly alleviate this problem.

This paper is organized as follows. In Section II, the system model and assumptions are given. Section III compares multiple unicast and multicast strategies considering a theoretical generic system using Shannon [8] with the Knopp&Humblett [6] channel model. In Section IV, we verify the coherence with the HSDPA context using a different radio channel model [1]. The multicast gain simulations for HSDPA are analyzed in Section V. Conclusions are drawn in Section VI.

II. THE SCENARIO DESCRIPTION

We restrict our study to a cell where N equivalent users require the same service. Users have the same average carrier to interference ratio. Considering equivalent UEs remains realistic (e.g. UEs grouped at a stadium or at a concert) and simplifies the evaluation of the used models.

Let γ_i be the carrier to interference ratio for user i . Due to the radio channel variations, γ_i is a random variable. Assuming the Node B is serving user UE_i , we define β_i as the largest

transport block size supported by UE_i . Let g be the function that relates β_i to the reported γ_i of the served user i ($\beta_i = g(\gamma_i)$), it is easy to see that g is a strictly increasing function. Let h be the associated inverse function (i.e. $\gamma_i = h(\beta_i)$).

Let $P_X(x)$ be the cumulative distribution function (CDF) of a random variable X . Similarly, $p_X(x)$ denotes the probability distribution function (PDF) of X . The CDF of β_i is then

$$P_{\beta_i}(x) = P_{\gamma_i}(h(x)). \quad (1)$$

A. Multiple unicast scenario

The advantage with unicast is the possibility to adjust transmission to the users radio conditions. At each TTI, the scheduler serves the UE that has the maximum bitrate capacity. Let δ_u be the maximum block size of the current transmission, we have then

$$\delta_u = \text{Max}_{\{i=1..N\}}(\beta_i). \quad (2)$$

As UEs are equivalent, the bandwidth is fairly shared among them. Each user is served every N TTIs on average. Note that no code multiplexing is used, i.e. the scheduler serves only one UE per TTI. The average bitrate per unicast user $R_{u,ucast}$ is then easily calculated to be

$$R_{u,ucast} = \frac{\mathbb{E}[\delta_u]}{ND_{TTI}}. \quad (3)$$

where D_{TTI} is the duration of a TTI. We recall that the average of a random positive variable X is given by

$$\mathbb{E}[X] = \int_0^{\infty} (1 - P_X(x))dx. \quad (4)$$

As $\{\beta_i\}_{i=1..N}$ are independent random variables and according to equation (2), the CDF of δ_u is given by

$$P_{\delta_u}(x) = P_{\beta}^N(x). \quad (5)$$

Combining equations (3), (4) and (5), we can deduce the average bitrate per unicast user

$$R_{u,ucast} = \frac{1}{ND_{TTI}} \int_0^{\infty} (1 - P_{\beta}^N(x))dx. \quad (6)$$

Using equation (1), we reformulate equation (6) as follows

$$R_{u,ucast} = \frac{1}{ND_{TTI}} \int_0^{\infty} (1 - P_{\gamma}^N(h(x))) dx. \quad (7)$$

B. Multicast scenario

We suppose all the UEs of the cell clustered in the same group. We use a conservative multicast approach to avoid packet losses for mobiles with low SNRs. Thus, at each TTI, the Node B serves all the UEs with the lowest bitrate capacity. Let δ_m be the lowest supported block size within the multicast group, we have then

$$\delta_m = \text{Min}_{\{i=1..N\}}(\beta_i) \quad (8)$$

We define $R_{u,mcast}$ as the average bitrate per multicast user

$$R_{u,mcast} = \frac{\mathbb{E}[\delta_m]}{D_{TTI}}. \quad (9)$$

Referring to equation (8), we compute the CDF of δ_m

$$P_{\delta_m}(x) = 1 - [1 - P_{\beta}(x)]^N. \quad (10)$$

Combining equations (4), (9) and (10), we can deduce the average bitrate per multicast user

$$R_{u,mcast} = \frac{1}{D_{TTI}} \int_0^{\infty} [1 - P_{\beta}(x)]^N dx. \quad (11)$$

From equation (1), it follows that

$$R_{u,mcast} = \frac{1}{D_{TTI}} \int_0^{\infty} [1 - P_{\gamma}(h(x))]^N dx. \quad (12)$$

C. Multicast gain

To compare multicast and multiple-unicast, we define Γ_m as the multicast gain

$$\Gamma_m = \frac{R_{u,mcast}}{R_{u,ucast}}. \quad (13)$$

The multicast gain can be also formulated as

$$\Gamma_m = \frac{N\mathbb{E}[\delta_m]}{\mathbb{E}[\delta_u]}. \quad (14)$$

III. STUDY OF A THEORETICAL GENERIC SYSTEM

We consider a generic system independently of the radio technology applied. To this end, we use the Shannon formula [8] that gives the maximum reachable system capacity.

A. Shannon formula

Shannon supposes a perfect error correcting system. It allows the computation of the maximum bitrate depending on the SNR ratios. If W is the available bandwidth, the maximum bitrate is then

$$R_{max}(bps) = W \log_2(1 + \gamma). \quad (15)$$

The transport block size is then derived as follows

$$g(\gamma) = WD_{TTI} \log_2(1 + \gamma). \quad (16)$$

Next, we can deduce the function h below

$$h(x) = 2^{\frac{x}{WD_{TTI}}} - 1. \quad (17)$$

B. Knopp-Humblett (K&H) model

In [6], K&H have proposed a reference radio channel model based on the following exponential distribution for γ

$$p_{\gamma}(x) = \begin{cases} \frac{1}{\bar{\gamma}} \exp(\frac{-x}{\bar{\gamma}}) & \text{if } x > 0 \\ 0, & \text{otherwise} \end{cases}$$

where $\bar{\gamma}$ is the average received SNR. We recall that the CDF of γ can be deduced by integrating its PDF. Hence

$$P_{\gamma}(x) = 1 - \exp(\frac{-x}{\bar{\gamma}}). \quad (18)$$

Then, combining equations (7) and (18), we can compute the mean bitrate per unicast user

$$R_{u,ucast} = \frac{1}{ND_{TTI}} \int_0^{\infty} \left(1 - [1 - \exp(\frac{-h(x)}{\bar{\gamma}})]^N\right) dx. \quad (19)$$

In the multicast case, equation (12) can be written as follows

$$R_{u,mcast} = \frac{1}{D_{TTI}} \int_0^\infty \exp\left(\frac{-Nh(x)}{\bar{\gamma}}\right) dx. \quad (20)$$

Using Shannon, we can substitute for h from equation (17) into equations (19) and (20). The mean bitrate per unicast user is then

$$R_{u,ucast} = \frac{1}{ND_{TTI}} \int_0^\infty (1 - [1 - \exp(\frac{-2^x W D_{TTI}}{\bar{\gamma}} + 1)]^N) dx. \quad (21)$$

as for the individual mean multicast bitrate

$$R_{u,mcast} = \frac{1}{D_{TTI}} \int_0^\infty \exp(\frac{-N2^x W D_{TTI}}{\bar{\gamma}} + N) dx. \quad (22)$$

C. Multicast gain using Shannon with K&H

Fig. 2 and Fig. 3 show the multicast gain for W and D_{TTI} fixed to 5 MHz and 2ms, respectively.

1) *gain vs $\bar{\gamma}$* : Fig. 2 presents Γ_m vs $\bar{\gamma}$ for various N . We see that the larger $\bar{\gamma}$, the more gain there is from multicast scheduling. It is also observed that the larger $\bar{\gamma}$ becomes, the greater the span in system gain becomes between different multicast group sizes.

2) *gain vs N* : Fig. 3 shows Γ_m vs N for different values of $\bar{\gamma}$. For $N=1$, it is trivial that Γ_m is equal to 1 whatever $\bar{\gamma}$ is. When N increases, the behavior of Γ_m depends on $\bar{\gamma}$ values. Two regions can be studied:

For low $\bar{\gamma}$ values: the greater N is, the smaller the gain. In fact, if N increases for poor channel quality, the probability of having a very low bitrate capacity within the multicast group is higher. Since the multicast strategy is conservative, the obtained mean bitrates are therefore close to zero. On the other hand, when N increases, the individual unicast bitrates become lower since the bandwidth is split between more users and then a lower bandwidth fraction is allocated to serve each unicast user. When the channel quality is bad, the group bitrate decrease has a higher impact than the reduction of unicast bandwidth fraction. Thus, multicast is less competitive than unicast and the resulting Γ_m is below 1.

For high $\bar{\gamma}$ values: the gain increases with N . In this case, multicast bitrate no longer suffers from frequent very small transport blocks. The increase of N affects unicast more since the bandwidth will be split between more users. On the other hand, if N increases, the minimum supported block size within a multicast group decreases too. When channel conditions are good enough, the decrease in the bandwidth fraction allocated to a unicast user is more dominant than the decrease of the supported bitrate within the multicast group, resulting in higher Γ_m values.

IV. STUDY OF THE HSDPA SYSTEM

In this section, we no longer consider a generic system. The used transport blocks sizes are those defined in the HSDPA specification [3]. We also consider a more complex radio channel model. That is to verify the coherence between the theoretical model and a more realistic model.

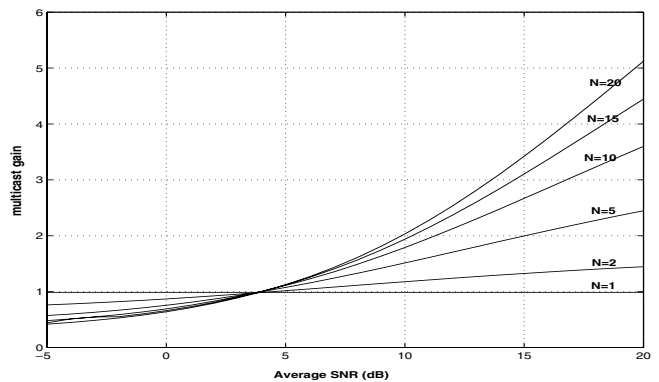


Fig. 2. Γ_m vs $\bar{\gamma}$ for different N

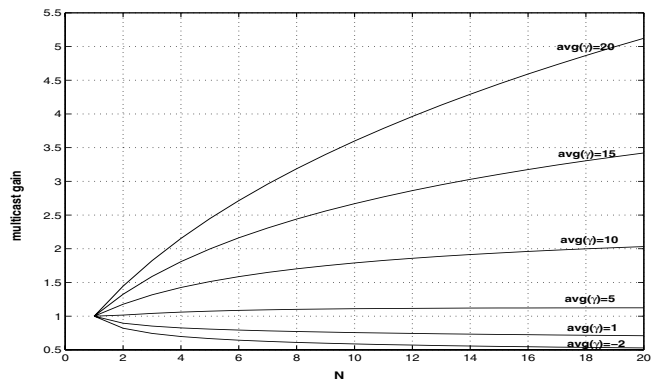


Fig. 3. Γ_m vs N for different values of $\bar{\gamma}$ (dB)

A. The considered radio channel model

The used radio channel model has been proposed in ‘‘Enhanced UMTS Radio Access Network extension for ns-2’’ (Eurane) simulator [1]. Let P_i be the transmit power to user i . The received power, denoted as P_r , is then given by

$$P_r = P_i h_{ij} \chi_{ij} \quad (23)$$

where h_{ij} is the path gain (including shadowing, distance loss and antenna gain) between user i and Node B j and χ_{ij} is the fast fading between user i and Node B j . The variable χ_{ij} is a random variable which represents Rayleigh fast fading, it has therefore an exponential distribution. The average of χ_{ij} is set equal to 1. The shadowing standard deviation is set equal to zero. Given these assumptions, all the users have the same signal average and the choice of the user to serve depends mainly on the random fast fading phenomenon. The signal to interference ratio received by user i connected to the reference Node B ($j=0$) is

$$\gamma_i = \frac{P_i h_{i0} \chi_{i0}}{I_{intra-cell,i} + I_{inter-cell,i} + N_{th}} \quad (24)$$

where $I_{intra-cell,i}$ and $I_{inter-cell,i}$ represent the intra-cell and inter-cell interference received by a user i , respectively. N_{th} is the background noise, it will be neglected. The internal interference received by UE_i at Node B 0 is

$$I_{intra-cell,i} = \alpha(P_{max} - P_i) h_{i0} \chi_{i0} \quad (25)$$

where α is the orthogonality factor and P_{max} is the total transmit power of each cell in the system. The received inter-cell interference is

$$I_{inter-cell,i} = \sum_{j=1}^M P_{max} h_{ij} \chi_{ij} \quad (26)$$

where M is the number of neighboring cells. The variable $I_{inter-cell,i}$ is the sum of exponential laws, so it tends to a Gaussian law when M is high. For simplicity, we assimilate it to a constant C . Finally, the received SNR reduces to

$$\gamma_i = \frac{P_i h_{i0} \chi_{i0}}{\alpha(P_{max} - P_i) h_{i0} \chi_{i0} + C} \quad (27)$$

Let $f(x)$ be

$$f(x) = \frac{P_i h_{i0} x}{\alpha(P_{max} - P_i) h_{i0} x + C} \quad (28)$$

f is bijective on R^+ and its inverse is given by

$$f^{-1}(x) = \frac{Cx}{P_i h_{i0} - \alpha(P_{max} - P_i) h_{i0} x} \quad (29)$$

The CDF of γ is given by

$$P_\gamma(x) = P_\chi(f^{-1}(x)). \quad (30)$$

As the fast fading χ has an exponential distribution, equation (30) is reformulated as follows

$$P_\gamma(x) = 1 - \exp\left(\frac{-Cx}{P_i h_{i0} - \alpha(P_{max} - P_i) h_{i0} x}\right). \quad (31)$$

B. Bitrate calculations considering an HSDPA system

The objective is to deduce the block size (β) from the SNR (γ) considering an HSDPA system. The rule is to derive the channel quality indicator (CQI) from γ and then β from CQI . Here, we detail the aforementioned steps:

The function that relates CQI to γ is given in [2]. A new formulation denoted as $qual$ is obtained when switching from a linear to a logarithmic scale and from a piecewise constant function to a continuous one

$$qual(\gamma) = \begin{cases} 0 & \text{if } \gamma \leq 0.025 \\ \frac{10 \log(\gamma)}{1.02} + 16.62 & \text{if } 0.025 < \gamma < 25.11 \\ 30 & \text{if } 25.11 \leq \gamma \end{cases}$$

Then, the block size (β) is computed for a given CQI . A mapping is defined in [3]. Using a quadratic approximation, we can express this mapping in form of a function M .

$$M(CQI) = \begin{cases} 183 & \text{if } CQI < 2 \\ (4.24CQI - 9.78)^2 + 182.2 & \text{if } 2 \leq CQI < 22 \\ 7154 & \text{if } 22 \leq CQI \leq 30 \end{cases}$$

Some adaptations have been done to make the function M continuous. Then, the function g that relates β to γ is deduced

$$g(\gamma) = M(qual(\gamma)). \quad (32)$$

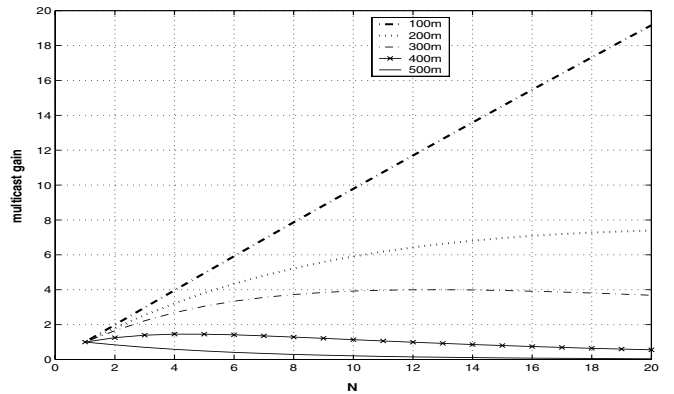


Fig. 4. Γ_m vs N for different $d_{UE-NodeB}$: numerical resolution of the analytical model for HSDPA

Finally, equation (32) becomes

$$g(\gamma) = \begin{cases} 183 & \text{if } \gamma < 0.032 \\ (41.5 \log \gamma + 60.68)^2 + 182.2 & \text{if } 0.032 \leq \gamma < 4.43 \\ 7154 & \text{if } 4.43 \leq \gamma \end{cases}$$

Function g is continuous and strictly increasing within $[0.032, 4.43]$. Then, its inverse h on this range is

$$h(x) = 10^{\frac{\sqrt{x-182.2}-60.68}{41.5}} \quad \text{if } 183 < x < 7154 \quad (33)$$

For the sake of simplicity, we define the following intermediate function

$$I(x) = \frac{Ch(x)}{P_i h_{i0} - \alpha(P_{max} - P_i) h_{i0} h(x)} \quad (34)$$

Then, according to equations (31) and (33), equation (7) becomes

$$R_{u,ucast} = \frac{1}{ND_{TTI}} \int_{183}^{7154} [1 - (1 - \exp(-I(x)))^N] dx. \quad (35)$$

As for equation (12), it becomes

$$R_{u,mcast} = \frac{1}{D_{TTI}} \int_{183}^{7154} \exp(-NI(x)) dx. \quad (36)$$

C. Multicast gain with HSDPA

Fig. 4 shows Γ_m vs N for different distances UE-Node B. The parameter P_i is fixed to 6.3. We note that Γ_m is the highest when UEs are near the Node B and gets lower when approaching the cell border. The multicast gain exceeds 1 when the distance-loss is low enough. This is coherent with the results of the theoretical case of Shannon/K&H in which Γ_m is higher than 1 for quite high SNR values (above around 3 dB).

To better assess performance, it is interesting to evaluate the limiting case of high average channel quality for which

$$\lim_{\bar{\gamma} \rightarrow \infty} \Gamma_m = N \quad (37)$$

In fact, when the channel quality is high enough, the supported block sizes reach a threshold value (7168 in HSDPA [3]). In this case, δ_m equals δ_u . Then, according to equation (14), we deduce that Γ_m tends to N .

TABLE I
SIMULATION PARAMETERS

| | |
|----------------------------------|------------------------------------|
| Simulation time | 20 sec |
| Frame period | 2ms |
| Power delay profiles | Typical Urban, Pedestrian A, rural |
| Velocity (kmh) | 50 (TU), 3 (Ped. A), 120 (rural) |
| UEs categories | 5 and 6 |
| BS Transmission power | 38 dBm |
| Power of Intra-cell interferants | 30 dBm |
| Inter-cell interference | -100 dBm |

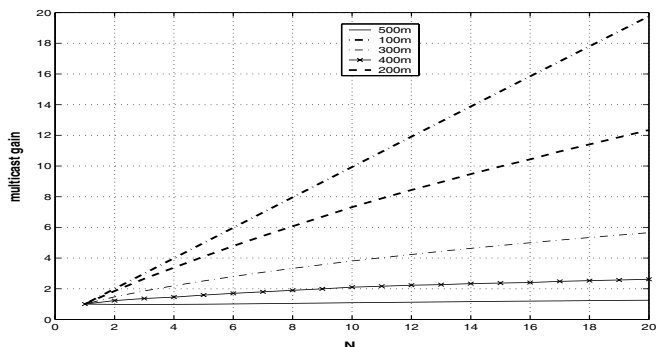


Fig. 5. Γ_m vs N for different distance-loss (simulations in a TU env.)

D. Forecast of the propagation environment impacts

When we fix N in equation (14), the multicast gain Γ_m increases if $\mathbb{E}[\delta_u]$ decreases while $\mathbb{E}[\delta_m]$ increases, which is equivalent to a reduction in the standard deviation of SNR. This may occur when the propagation environment is characterized by a fast fading having a low dynamicity. Tests considering different environments (Pedestrian A, rural, Typical Urban (TU) etc.) will confirm this statement.

V. SIMULATION RESULTS FOR HSDPA

A. Simulation parameters

Simulation parameters are listed in Table I. The “Enhanced UMTS Radio Access Network extension for ns-2” (Eurane) simulator [1] has been used. It implements the channel model and the bitrate derivation mechanism described in Sections IV-A and IV-B, respectively.

B. Simulated multicast gain with HSDPA

Fig. 5 shows the multicast gain for different distances from the Node B. As it has been found in the HSDPA analytical model (section IV), the gain is the highest when UEs are near the Node B and gets lower when moving toward the cell border. At 100 m, SNR values are mapped to the maximum block size value (7168 bits/TTI [3]) for both unicast and multicast. Thus, Γ_m reaches 20 with 20 users. When terminals go further, the gain from using multicast decreases. At the cell border (500m), multicast brings no tangible interest compared to unicast, Γ_m is around 1. Fig. 5 shows that Γ_m increases with N for low distance-loss values, which is coherent with the results of the analytical model for HSDPA and also Shannon with K&H model.

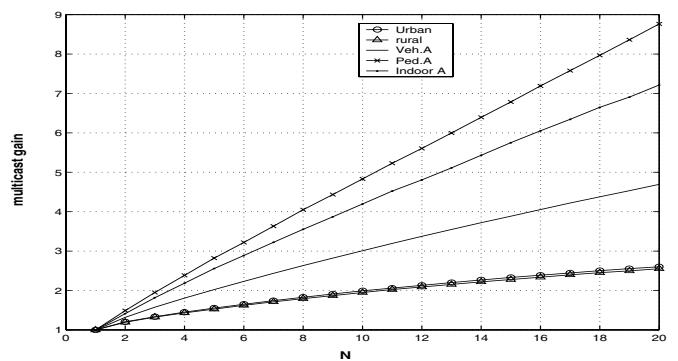


Fig. 6. Γ_m for different environments (at 400 m)

Simulations of Γ_m for different propagation environments are shown in Fig. 6. Gains are higher for environments with low channel dynamicity (like Ped. A and Indoor A). In fact, the standard deviation of fast fading is less important in these environments (2.19 and 2.86 dB in Ped. A and Indoor A, respectively) than in the TU (5.81 dB), rural (5.81 dB) and vehicular (4.36 dB) cases. This leads to a low standard deviation of the SNR and then a higher multicast gain.

VI. CONCLUSIONS

In this study, we have compared multiple-unicast to conservative multicast scheduling in the framework of both a generic theoretical system and an HSDPA system. Taking the mean bitrate per user as the performance metric, we have shown that multicast can largely outperform unicast for acceptable channel quality. Having proved the merits of multicast scheduling, we have laid out the foundation of the necessity to investigate more in multicast schedulers design.

In summary, we have verified that the multicast gain depends on the multicast group size, the mean SNR (equivalently the distance from the Node B) and also the propagation environment. Future work will generalize the study to UEs with different average SNRs by using a convenient group clustering and evaluate more enhanced scheduling schemes.

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