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Maximum-weight scheduling with hierarchical modulation for lower delay ☆

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ABSTRACT

In this paper, hierarchical modulation is used in conjunction with maximum-weight scheduling to achieve lower transmission delays. Via hierarchical modulation, the scheduled user has the option to transmit to two users simultaneously. In order to reflect service differentiation schemes used in upper layers, a scenario in which each user generates packets with different priority levels is considered. It is assumed that as long as there are high priority packets waiting in the scheduled user's queue, lower priority packets cannot be transmitted. It is shown that, using hierarchical modulation in the presence of packet prioritization, average delay of low priority traffic can be reduced while achieving higher throughput. In the absence of packet prioritization, using hierarchical modulation lowers packet transmission delays without any loss in throughput. The effect of multiple access interference is also investigated. It is shown that both single and two-layer schemes have similar average spatial reuse factors.

1. Introduction

At the physical layer, superposition coding is suggested for broadcast channels to attain reliable communication with two receivers simultaneously [2]. In superposition coding, messages are layered on each other. This way, the destination with worse channel conditions can reliably decode its own message at the base layer and after decoding the message in the base layer, the destination with better channel conditions can understand its own in the enhancement layer. Hierarchical modulation (also known as embedded, asymmetrical, non-uniform or multi-resolution modulation) is a practical way of applying superposition coding [3–6]. In practice, hierarchical modulation is used for video transmission in the digital video broadcasting-terrestrial (DVB-T) standard [7], but it is not yet implemented in cellular or ad hoc networks.

In hierarchical modulation, channel code, assigned power level, signal constellation type, constellation size and symbol mapping can be chosen independently for each layer to control the probability of error at each layer separately. Allowing non-uniform spacing between signal points on the signal constellation, hierarchical modulation protects base layer bits more than enhancement layer bits. While the user with better channel conditions can reliably demodulate both base and enhancement layer bits, the user with poor channel conditions can only recover the base layer. The achievable rate region of the Gaussian broadcast channel with practical constellations and channel coding schemes are investigated in [8,9]. In [10–12], the authors use hierarchical constellations to transmit to two users simultaneously. The proposed adaptive modulation method is opportunistic in the sense that a second user is superposed on the first, only if the first user can transmit with the already assigned rate in the presence of the interlayer interference caused by the second user. This way, channel access probability is almost doubled without any loss in spectral efficiency.

In a wireless communication network, via scheduling the dynamic nature of the communication medium can be exploited for enhanced throughput, higher stability, lower delay or improved fairness among users. For example, proportionally fair scheduling prioritizes fairness [13], whereas maximum-weight scheduling emphasizes maximum throughput while keeping the system stable [14]. In opportunistic scheduling methods, the user with the best channel quality is selected to improve system performance. However, in all single-user scheduling methods channel access probability is low, leading to high waiting times and long queues. To prevent such adverse effects, multi-user transmission

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techniques and scheduling algorithms can be designed jointly [15,16]. In [15], network stability problem is studied, when ideal superposition coding schemes of [2] are used in conjunction with maximum-weight scheduling [14]. In [16], a greedy scheduler allows for multiple-access and broadcast transmissions in addition to point-to-point links. In [17], the authors perform joint routing and scheduling, using successive interference cancelation, superposition coding and dirty paper coding in wireless mesh networks.

In the literature, there are only a few papers that look into joint modulation and scheduling design. In [18], queueing delays and buffer distributions in a network are analyzed for two-best user opportunistic and hybrid two-user scheduling schemes, when the rate-adaptive hierarchical modulation scheme of [11] is used. In our work, we investigate practical hierarchical modulation schemes and maximum-weight scheduling jointly. Instead of single-user scheduling only, the transmitter can choose to transmit to two users simultaneously. In this case, the scheduler considers the queue lengths and transmission rates to both receivers and computes the weight accordingly.

In [1], assuming all generated packets in the network are equally important, it has been shown that the probability of choosing hierarchical transmission schemes is more than 50%. This shift from single-layer transmission schemes presents itself as lower delays and shorter queue lengths without any throughput loss.

The contributions of this paper can be summarized as follows:

- Assuming that there are four different types of packets at four different priority levels and that the lower priority packets cannot be transmitted, while there are higher priority packets in the queue, it is shown that two-layer transmission schemes benefit lower priority level packets significantly, in terms of *both* throughput and delay.
- Including physical layer interference and allowing for multiple transmitters in a time slot, the average spatial reuse factor is computed and it is shown that using hierarchical modulation does not result in unforeseen expenses at the multiple access layer: both single-layer and two-layer schemes have similar spatial reuse factors.

The organization is as follows: Section 2 introduces the system model, Section 3 explains the transmission schemes in use, Section 4 presents the numerical results, and Section 5 concludes the paper.

2. System model

In this paper, we study a wireless network which consists of N nodes uniformly distributed in a pre-determined area. We assume the network is connected in the sense that two nodes are connected with a link, if the average signal to noise ratio (SNR) of the link supports binary phase shift keying (BPSK) transmission; i.e. the average SNR is above the SNR threshold for a given target bit error probability. This model is equivalent to link layer connectivity. Note that, even if two nodes are connected, for a particular channel gain the instantaneous SNR can be low and reliable communication is not possible even with BPSK transmission.

We study two transmission scenarios. In the first scenario, each user node creates data packets for each one of its K_i neighbor nodes according to Poisson distribution with parameter $\lambda_i = \lambda/K_i$. Here λ is the average number of packets node i generates, $i \in \{1, 2, \ldots, N\}$. All data packets are equally important. In the second scenario, each user node creates four types of data packets at four different priority levels, according to Poisson distribution with parameter $\lambda_i^{(\rho)}, \rho = \{1, 2, 3, 4\}$. Here ρ indicates the priority level. Priority levels are ordered and level 1 has the highest priority. The average number of data packets node i generates is $\lambda_i = \lambda_i^{(1)} + \lambda_i^{(2)} + \lambda_i^{(3)} + \lambda_i^{(4)}$ and $\lambda_i = \lambda/K_i$.

A TDMA based medium access scheme is assumed. The scheduled user transmits one physical layer packet in each time slot. Note that one physical layer packet can be composed of multiple data packets depending on the chosen constellation. Time slots are denoted with $n, n = 1, 2, \ldots$ and each time slot is N_{phy_pkt} symbols long. Symbol indices are denoted with $m, m = 1, 2, \ldots, N_{phy\_pkt}$. We assume error correction codes are used and correct N_{fec} bits of error in every N_{data_pkt} bits transmitted.

When node i communicates with node j, the received signal at node $j, j = 1, 2, \ldots, N$, at time slot n and at symbol index m is given as

$$y_{j,n,m} = \sqrt{f(\Delta_{ij})}\sqrt{E_i}h_{ij,n}x_{i,n,m} + z_{j,n,m} \quad (1)$$

where $x_{i,n,m}$ and $\sqrt{E_i}$ respectively denote the modulated source symbol and the average symbol energy at node i. Modulated source symbols are normalized to have unit average energy for each modulation scheme and the average symbol energy is the same for all transmitting nodes. The channel gain and the distance between nodes i and j are respectively denoted with $h_{ij,n}$ and Δ_{ij}. There is path loss and the received power scales with $f(\Delta_{ij})$. There is Rayleigh fading in all channels and the channel gain magnitude squares, $|h_{ij,n}|^2$, are independent exponential random variables with unit mean for all i, j and n. The channel gain is constant over a time slot. The variable $z_{j,n,m}$ is the noise at node j. The noise components $z_{j,n,m}$ are independent and identically distributed (i.i.d.) complex Gaussian random variables with zero mean and variance N_0 for all j, n and m. Finally, we assume there is receiver side channel state information and $f(\Delta_{ij}), E_i$ and $h_{ij,n}$ are known perfectly at node j. The transmitter, on the other hand, knows Δ_{ij} and the noise distribution at the receivers. Thus, it is only informed about the average received SNR at node j.

3. Transmission schemes

In this paper, we compare using single-layer and hierarchical (two-layer) modulation techniques under maximum-weight scheduling. Two-layer modulation is a practical way of superposition coding suggested for broadcast channels [2]. One can send two different data packets to two different receivers by using hierarchical modulation. As an example 4/8-hierarchical quadrature amplitude modulation (QAM) is shown in Fig. 1. When two-layer modulation is used, base and enhancement layer bits are superposed on each other and decoding is performed in layers. When base layer bits are destined to the first receiver and enhancement layer bits are for the second receiver, the first receiver only decodes base layer bits, treating enhancement layer bits as noise. On the other hand, the second receiver either decodes both layers jointly or performs decoding in layers, i.e. first decodes base layer bits, then after successive cancelation, decodes enhancement layer bits.

In this work, we use M-QAM, $M \in \{2, 4, 8, 16, 32, 64\}$ as single-layer modulation techniques. Transmission rates corresponding to these modulation schemes are respectively {1,2,3,4,5,6} bits per symbol. When hierarchical transmission is allowed, 2/4, 2/8, 4/8, 2/16, 4/16, 8/16, 4/64 and 16/64-QAM two-layer modulation schemes, with base and enhancement layer transmission rates respectively equal to {(1,1), (1,2), (2,1), (1,3), (2,2), (3,1), (2,4), (4,2)} bits/symbol, are also possible in addition to the above listed single-layer modulation techniques.[1]

[1] In the following, we abuse the expression "hierarchical transmission". It refers to an opportunistic technique, where both single-layer and two-layer signal constellations can be in use.

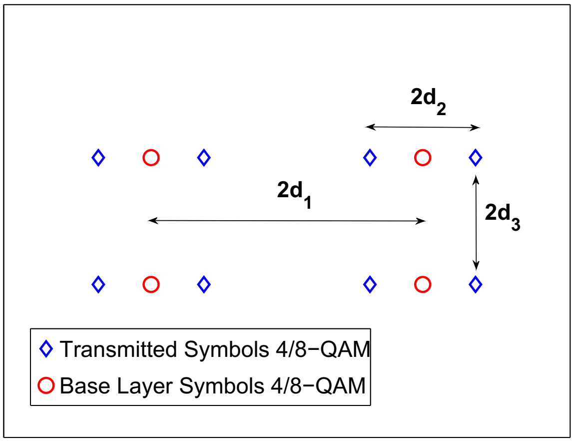

Fig. 1. The signal constellation for 4/8-QAM.

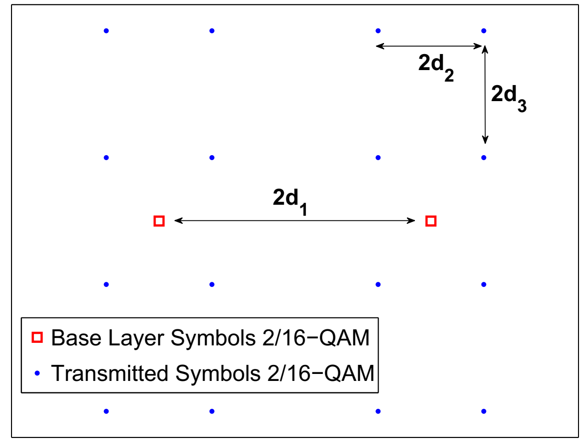

Fig. 2. The signal constellation for 2/16-QAM.

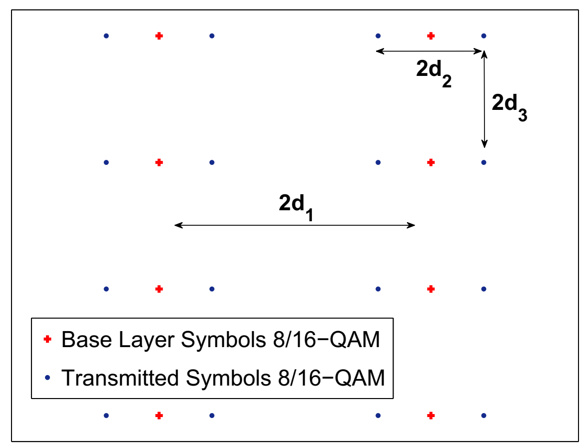

Fig. 3. The signal constellation for 8/16-QAM.

The transmission scheme 2/4-QAM is identical to 4-QAM, except each dimension carries 1 bit per symbol for each user. The signal constellation for 2/8-QAM can be thought of as the superposition of two constellations, BPSK with minimum distance $2d_1$ and 4-QAM with minimum distance $2d_2$. For 2/8-QAM, we assume $d_1/d_2 = 2$. The signal constellations for 4/8, 2/16 and 8/16-QAM are shown in Figs. 1–3, respectively. For 4/8-QAM $d_3/d_2 = 2$ and $d_1/d_2 = 2$, for 2/16-QAM, $d_1/d_2 = 2, d_2/d_3 = 1$, and for 8/16-QAM $d_1/d_2 = 2$ and $d_3/d_2 = 1$. Similarly, 4/16-QAM is the superposition of two 4-QAM signal constellations, each with minimum distances $2d_1$ and $2d_2$, where $d_1/d_2 = 2$. The signal constellations 4/64 and 16/64-QAM are similar to 4/16-QAM and for both we assume $d_1/d_2 = 2$.

Physical layer packets are assumed to have $N_{phy\_pkt} = 240$ symbols. For error correction coding, we assume that encoded packets are $N_{data\_pkt} = 240$ bits long and $N_{fec} = 20$ errors can be corrected. Moreover, the target packet error rate (PER) is equal to 0.05. Table 1 shows the threshold SNR values for the given target PER for the modulation schemes in use. For single-layer transmission from node i to j, node i compares $f(\Delta_{ij})E_i/N_0$ with γ_{th} in Table 1 to find possible transmission rates. For two-layer modulation schemes, when user j and k data are respectively transmitted in base and enhancement layers, we require both $f(\Delta_{ij})E_i/N_0$ and $f(\Delta_{ik})E_i/N_0$ to be respectively larger than $\gamma_{b,th}$ and $\gamma_{e,th}$ in Table 1. As the transmitter is not informed about the instantaneous channel gains $h_{ij,n}$ or $h_{ik,n}$, reliable transmission is not guaranteed even if average received SNR(s) are larger than the listed threshold(s). Once the possible transmission rates are determined, maximum-weight scheduling is used to select the user that will transmit.

3.1. Single priority level

For the first scenario, at time slot n, for single-layer transmission

$$w_{ij,n} = (1 - PER_{R^S_{ij}})q_{ij,n}R^S_{ij} \tag{2}$$

and for hierarchical modulation

$$w_{ijk,n} = (1 - PER_{R^{H(b)}_{ijk}})q_{ij,n}R^{H(b)}_{ijk} + (1 - PER_{R^{H(e)}_{ijk}})q_{ik,n}R^{H(e)}_{ijk}. \tag{3}$$

Here $w_{ij,n}$ and $w_{ijk,n}$ respectively denote the weights for transmitting to node j and to nodes j and node k simultaneously, $q_{ij,n}$ is the queue length for packets from node i to node j and $PER_x, x \in \{R^S_{ij}, R^{H(b)}_{ijk}, R^{H(e)}_{ijk}\}$, denotes the packet error probability corresponding to the transmission rate x. Note that, PER_x is also a function of the average received SNR, yet to keep the notation simple, we do not indicate this relation. The transmission rates $R^S_{ij}, R^{H(b)}_{ijk}$ and $R^{H(e)}_{ijk}$ are in bits per symbol and respectively denote the instantaneous rates for single-layer modulation, for two-layer modulation-base layer and for two-layer modulation-enhancement layer.

3.2. Four different priority levels

For the second scenario with four different priority levels, lower priority packets should not be sent while the selected user still has higher priority packets. In the scheduling algorithm, we impose this rule via the coefficient $\nu^{(\rho)}, \{\nu^{(1)} \gg \nu^{(2)} \gg \nu^{(3)} \gg \nu^{(4)}\}$ and calculate the weight from user i to j for single-layer transmission at time slot n as

$$w_{ij,n} = (1 - PER_{R^S_{ij}})\sum_{\rho=1}^{4}\nu^{(\rho)}q^{(\rho)}_{ij,n}\mu^{S(\rho)}_{ij}. \tag{4}$$

In (4), $q^{(\rho)}_{ij,n}$ is the queue length and $\mu^{S(\rho)}_{ij}$ is the transmission rate for level-ρ priority packets from node i to node j. The rates $\mu^{S(\rho)}_{ij}$ has to satisfy

$$\sum_{\rho=1}^{4}\mu^{S(\rho)}_{ij} \leqslant R^S_{ij}. \tag{5}$$

In other words, the sum rate over all priority levels cannot exceed the transmission rate of any user.

Table 1
Threshold SNR values for the modulation techniques in use.

Single-layer (M-QAM)	2	4	8	16	32	64		
Thresholds [dB], γ_{th}	12.6	15.59	19.65	21.45	24.95	28.2		
Two-layer (M_1/M_2-QAM)	2/4	2/8	4/8	2/16	4/16	8/16	4/64	16/64
Base layer [dB], $\gamma_{b,th}$	15.9	17.4	19.4	19.5	19.6	21.05	21.1	25.8
Enhancement layer [dB], $\gamma_{e,th}$	15.9	21.05	21.6	22.55	23.8	23.7	29.4	30.3

When hierarchical modulation is used in the second scenario

$$w_{ijk,n} = \left(1 - PER_{R_{ijk}^{H(b)}}\right)\sum_{\rho=1}^{4} v^{(\rho)} q_{ij,n}^{(\rho)} \mu_{ijk}^{H(b)(\rho)} + \left(1 - PER_{R_{ijk}^{H(e)}}\right)\sum_{\rho=1}^{4} v^{(\rho)} q_{ik,n}^{(\rho)} \mu_{ijk}^{H(e)(\rho)}, \quad (6)$$

and the total transmission rate at the base and enhancement layers respectively have to satisfy

$$\sum_{\rho=1}^{4} \mu_{ijk}^{H(b)(\rho)} \leqslant R_{ikl}^{H(b)}, \quad \text{and} \quad \sum_{\rho=1}^{4} \mu_{ijk}^{H(e)(\rho)} \leqslant R_{ikl}^{H(e)}. \quad (7)$$

This means that both base and enhancement layers can be composed of different priority level bits. For example, let the number of queued packets from node i to j and i to k are both 1, 1, 0 and 0 for priority levels 1 to 4, respectively. If 4/16 QAM is feasible, then all the packets in these queues are arranged into one physical layer packet. However, if 4/16 QAM is not achievable, but the largest feasible modulation scheme is 2/4 QAM, then only the first priority data packets for users j and k are transmitted. Second priority data packets are left in their respective queues. As the inter-node distances remain fixed for the whole communication period, maximum possible transmission rates are the same for all time slots for both scenarios. However, depending on the number of awaiting packets, the actual transmission rate, the corresponding PER, and thus the weight for a given slot can change. Among all weights, in each time slot n, the scheduler determines the maximum weight, thus the transmitting and receiving users. Note that for hierarchical modulation schemes, the weights $w_{ijk,n}$ and $w_{ikj,n}$ are not necessarily the same, and maximum weight scheduling also decides on which users to serve at the base and enhancement layers.

3.3. Spatial reuse

Although hierarchical modulation has the potential to lower transmission delays, it poses an issue at the multiple access layer. When hierarchical modulation is used, transmission to two nodes takes place simultaneously. For successful transmission to both receivers, the users in the neighborhood of both receivers must be kept silent. If physical layer interference is a problem, this can mean a smaller spatial reuse factor. Therefore, in this paper, we also compare the spatial reuse factors for single-layer and hierarchical communication schemes for the first scenario. When node i transmits to node j, the average signal to interference-noise ratio at node j is defined as

$$SINR_j = \frac{f(\Delta_{ij})E_i}{\sum_{i'=1, i' \neq i}^{K} f(\Delta_{i'j})E_{i'} + N_0} \quad (8)$$

Here, K is the number of interfering transmitters.

In the multiple access algorithm, the first user is chosen randomly. Among its neighbors, the receiving node(s) are determined according to the weights defined in (2) and (3), and the node(s) that result in the maximum weight are chosen. As there are no other users scheduled at this moment, the interference term in the denominator in (8) is 0. In each iteration of the algorithm, a new transmitter is added to the list of scheduled users, provided that the additional average interference it causes to the previously scheduled transmitters do not decrease the already determined transmission rates. The iterations continue until no other transmitter can be scheduled without harming the previously selected rates. As the transmitters are not informed about the instantaneous channel state information, they have to rely on average channel conditions; i.e. the transmission rates described in the above multiple user scheduling take only the average interference into account. The actual interference experienced by each user is a sum of multiple independent random variables. When multiple independent random variables are added, the total variance becomes the sum of individual variances. Thus, the instantaneous interference value can deviate more from the average than a single random variable does. This means that in practice scheduled transmissions are unreliable more often than the average performance suggests. In order to mitigate this issue, in spatial reuse computations, we use threshold values (γ_{th}^{margin}) which are 3 dB higher than γ_{th} listed in Table 1.

4. Numerical results

In our first set of simulations, we assume there are $N = 10$ nodes in an area of 800×800 m^2, $E_i/N_0 = 15$ dB for all i and the function $f(\Delta_{ij})$ in (1) is defined as

$$f(\Delta_{ij}) = \begin{cases} 8 \times 10^{-3}, & \Delta_{ij} \leqslant 1 \text{ m} \\ 10^{(-2\log_{10}\Delta ij) - \log_{10}(8\times10^{-3})}, & 1m < \Delta_{ij} \leqslant 400 \text{ m} \\ 10^{(-4\log_{10}\Delta ij) + 2\log_{10}400 - \log_{10}(8\times10^{-3})}, & 400 \text{ m} < \Delta_{ij} \end{cases} \quad (9)$$

For the first scenario, we assume $\lambda = 0.19$ data packets/slot. For the second scenario, each user creates priority level 1 packets the least and priority level 4 packets the most and the packet generation parameters are set to $\lambda^{(1)} = 0.03, \lambda^{(2)} = 0.06, \lambda^{(3)} = 0.12, \lambda^{(4)} = 0.24$. These parameters are chosen to keep the system stable for priority levels 1, 2 and 3 but not necessarily for level 4. This level is used for best effort services and does not offer any quality of service guarantee at the application layer.

The following results are averaged over 100 connected graphs for both scenarios and the simulation time is 1000 slots. Fig. 4 depicts the total average transmitted packets in the system for the first scenario. We can observe that allowing for hierarchical signal constellations in the maximum weight scheduling algorithm does not reduce the total average throughput. This is an interesting observation, because in the Gaussian broadcast channel, sum throughput is the largest if the transmitter communicates with the receiver with better channel conditions *only* [2]. When transmission to both users take place simultaneously, the achievable sum rate is lower. We note that the setting for the aforementioned result corresponds to a continuous signal constellation, where any point in two dimensional space is possible, while we consider a set of practical constellations with finite number of signal points.

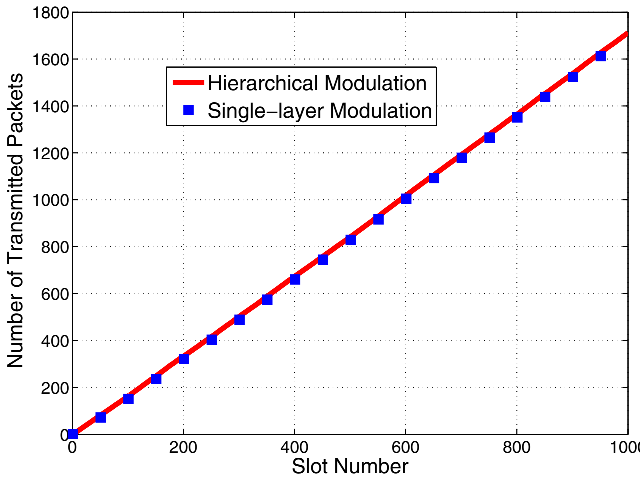

Fig. 4. Average number of total transmitted packets, single-layer vs. hierarchical modulation, only single priority level packets exist.

We also investigate how long the packets wait in the queue before they are transmitted for the first scenario. The cumulative distribution function (CDF) of packet delay, averaged over users and graphs is shown in Fig. 5. We observe that including two-user scheduling significantly improves the average delay each packet observes. The improvement is 28% for 10 slot delays.

For the second scenario, using hierarchical modulation also improves the total throughput especially for the third and fourth priority level packets. As both single-layer and hierarchical modulation schemes treat the first priority level packets the same way ((i) they are always sent the first with the highest possible rate and (ii) while there are still first priority level packets waiting, no other type of packet is sent) their average throughput are the same for $\rho = 1$. Similarly, second priority level packets do not experience significant gains. However, using hierarchical modulation enhances the total throughput of the third and fourth priority level packets respectively 9% and 13% as shown in Fig. 6. In Fig. 6, we also observe that the total number of packets waiting in the queue is significantly lower for two-user scheduling than that of the single user scheduling scheme.

When compared with the first scenario, gains due to hierarchical modulation are more significant in the second scenario. We conclude that asymmetry in the network (in this case it is in priority levels) favors hierarchical transmission even more. This observation also agrees with information theoretical results on broadcast channels [2]. In a two user degraded Gaussian broadcast channel, the capacity region reduces to the time division region when the two users observe statistically equivalent channels.

In addition to these, for the second scenario we also analyze how long different priority level packets wait in the queue. The CDF of the second and third priority level packets are illustrated in Fig. 7. In this figure, we observe that including two-user scheduling significantly improves the average delay each packet observes. Using hierarchical modulation enhances the delay performance about 12% (30%), when targeted delay of priority level 2 (3) is determined as 10 (100) slots. As both single and two-layer modulation schemes immediately send first priority level packets, their delay performances are identical. Since the network is not stable for priority level 4 packets, which represents best effort type of traffic, average delay values for these packets are not meaningful and they are not included in Fig. 7.

Table 2 shows the usage percentage of all modulation techniques in use for the first and second scenarios. In the first scenario, if single-layer modulation is used alone, we observe that BPSK, 4-QAM, 8-QAM and 16-QAM are used in 100% of all cases. On the

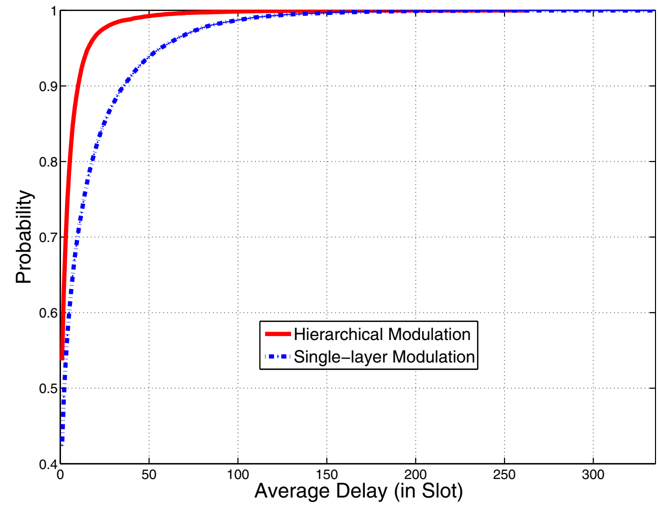

Fig. 5. Cumulative distribution function of packet delay, only single priority level packets exist.

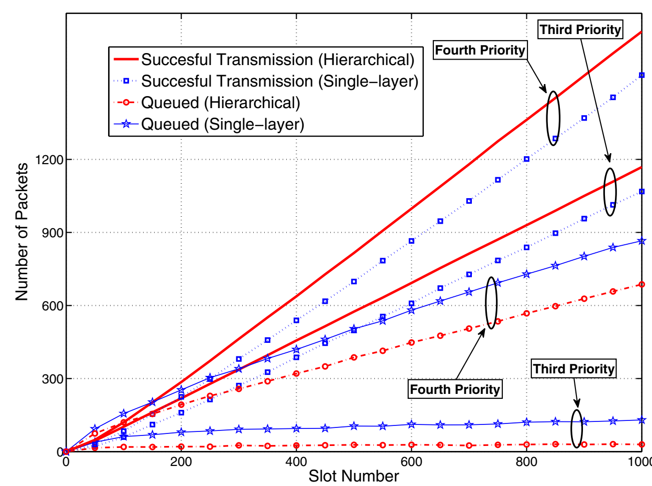

Fig. 6. Average number of total packets in the queues and transmitted packets for priority levels 3 and 4.

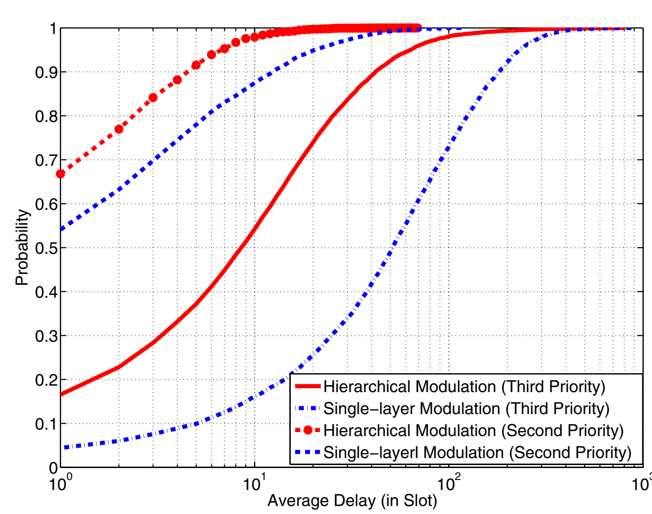

Fig. 7. Cumulative distribution function of packet delay for second and third priority level packets.

Table 2
Usage percentage of modulation schemes for single and four priority level packets.

Single priority level														
Hierarchical(QAM)	2	4	8	16	32	64	2/4	2/8	4/8	2/16	4/16	8/16	4/64	16/64
Percentage (%)	27.8	17.8	1.1	0	0	0	38.2	4.8	9.3	1	0	0	0	0
Single-layer(QAM)	2	4	8	16	32	64								
Percentage (%)	39.1	54.7	5.7	0.5	0	0	–	–	–	–	–	–	–	–
Four different priority levels														
Hierarchical(QAM)	2	4	8	16	32	64	2/4	2/8	4/8	2/16	4/16	8/16	4/64	16/64
Percentage (%)	6	4.9	0.42	0.25	0.17	0.18	13.4	11.9	5.1	6.83	12.3	11.02	17.4	10.1
Single-layer(QAM)	2	4	8	16	32	64								
Percentage (%)	11.615	23.85	16.57	18.47	12.69	16.8	–	–	–	–	–	–	–	–

other hand, in hierarchical transmission, two-layer and single-layer modulations are respectively used in 53.3% and 46.7% of the time. In other words, broadcasting to two users does not incur any throughput loss (as opposed to the Gaussian broadcast channel results in [2]) and the way the system operates changes significantly. In the second scenario, two-layer signal constellations are used in 88.1% of the time. Moreover, constellation sizes larger than 4/16 QAM are never used in the first scenario, but their usage percentage rises to 50.82 in the second scenario. Sending first priority level packets only is a complete waste of resources. One can almost always append other packets to the transmission of a first priority level packet, improving the system throughput and lowering delays.

We also investigate spatial reuse for the first scenario in a dense wireless ad-hoc network. The spatial reuse setup takes the physical layer interference into account and shows the number of transmitters that can be scheduled simultaneously in the same time slot. In the simulations it is assumed that there are 100 user nodes in the network in an area of $40 \times 40\ \text{km}^2$. The value $E_i/N_0 = 15$ dB, $f(\Delta_{ij})$ is the same as (9), and the results are averaged over 20 different connected graphs. We find that the spatial reuse factors for single user and two-user scheduling are respectively equal to 5.35 and 5.39 with standard deviations 1.12 and 0.882, where the maximum spatial reuse factor for each of the simulated graphs is observed to be equal to 8. The two spatial reuse factors are almost identical because transmission to one of the receivers in the two-user setting almost always deters the other selected receiver from any other single-user transmission/reception. Overall, we conclude that two-user scheduling improves the delay performance without any loss in average spatial reuse factor.

5. Conclusion

In this paper, we study maximum-weight scheduling, where broadcasting to two users is possible in addition to single user transmission. For broadcasting purposes hierarchical modulation and successive cancelation demodulation are used. We consider two scenarios: (1) all generated packets have equal importance and (2) packets can have four different priority levels. It is shown that in both cases hierarchical modulation is utilized for more than 50% of the time, resulting in lower delays and shorter queue lengths when compared with single-user scheduling with single-layer modulation schemes. Moreover, hierarchical modulation results in the same (scenario 1 and scenario 2 first and second priority level packets) or higher throughput (scenario 2, third and fourth priority level packets) when compared with single-layer transmission. Finally, we incorporate the effects of interference into our simulation and compute the spatial reuse factor for scenario 1. We find that hierarchical modulation does not incur any extra loss at the multiple access layer and attains a similar spatial reuse factor as single-layer transmission.

As a conclusion, joint physical layer and multiple access layer design via two-user scheduling improves delay performance without any loss in total throughput or in average spatial reuse factor. Multiuser modulation schemes have a high potential to improve throughput, transmission delays, buffer occupancy and fairness. These gains are more emphasized when there is asymmetry in the network. In this paper, we only considered the effect of unequal priority levels. Future work includes studying asymmetry in bit error requirements and in packet lengths of the two receiving users.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.aeue.2016.06.005.

References

[1] Yalcin AZ, Yuksel M, Onat F, Aktas D, Numanoglu T, Kolagasioglu A. Maximum-weight scheduling with hierarchical modulation. 2014 Iran Workshop on Communication and Information Theory (IWCIT). p. 1–5. http://dx.doi.org/10.1109/IWCIT.2014.6842509.

[2] Cover T. Broadcast channels. IEEE Trans Inf Theory 1972;18:2–14.

[3] Ungerboeck G. Channel coding with multilevel/phase signals. IEEE Trans Inf Theory 1982;28:55–67.

[4] Calderbank AR, Seshadri N. Multilevel codes for unequal error protection. IEEE Trans Inf Theory 1993;39:1234–48.

[5] Morelos-Zaragoza RH, Fossorier M, Lin S, Imai H. Multilevel coded modulation for unequal error protection and multistage decoding. I. symmetric constellations. IEEE Trans Commun 2000;48:204–13.

[6] Isaka M, Fossorier M, Morelos-Zaragoza R, Lin S, Imai H. Multilevel coded modulation for unequal error protection and multistage decoding. II. asymmetric constellations. IEEE Trans Commun 2000;48:774–86.

[7] V. ETSI, EN 3000 744, Digital video broadcasting (DVB): framing structure, channel coding and modulation for digital terrestrial television; 2004.

[8] Sun T, Wesel R, Shane M, Jarett K. Superposition turbo TCM for multirate broadcast. IEEE Trans Commun 2004;52:368–71.

[9] Deshpande N, Rajan BS. Constellation constrained capacity of two-user broadcast channels. IEEE Global Telecommunications Conference, GLOBECOM 2009. p. 1–6.

[10] Hossain MJ, Alouini M-S, Bhargava V. Multi-user opportunistic scheduling using power controlled hierarchical constellations. IEEE Trans Wireless Commun 2007;6:1581–6.

[11] Hossain MJ, Alouini M-S, Bhargava VK. Rate adaptive hierarchical modulation-assisted two-user opportunistic scheduling. IEEE Trans Wireless Commun 2007;6:2076–85.

[12] Hossain MJ, Alouini M-S, Bhargava VK. Two-user opportunistic scheduling using hierarchical modulations in wireless networks with heterogenous average link gains. IEEE Trans Commun 2010;58:880–9.

[13] Tse D, Viswanath P. Fundamentals of Wireless Communication. Cambridge University; 2004.

[14] Tassiulas L, Ephremides A. Stability properties of constrained queueing systems and scheduling policies for maximum throughput in multihop radio networks. IEEE Trans Autom Control 1992;37:1936–48.

[15] Karaca M, Ercetin O. Optimal scheduling and resource allocation using hierarchical modulation in wireless networks. IEEE 2011 Eighth International Conference on Wireless and Optical Communications Networks (WOCN). p. 1–5.

[16] Sridharan A, Koksal CE, Uysal-Biyikoglu E. A greedy link scheduler for wireless networks with Gaussian multiple-access and broadcast channels. IEEE/ACM Trans Networking 2012;20:100–13.

[17] Shabdanov S, Mitran P, Rosenberg C. Cross-layer optimization using advanced physical layer techniques in wireless mesh networks. IEEE Trans Wireless Commun 2012;11:1622–31.

[18] Hossain MJ, Alouini M-S, Bhargava V. Channel access delay and buffer distribution of two-user opportunistic scheduling schemes in wireless networks. IEEE Trans Commun 2010;58:2077–87.