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Cluster Modulation: A Generalized Modulation Scheme Leading to NOMA or Adaptive Modulation

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Abstract

The need for higher data rate and higher systems capacity leads to several solutions including higher constellation size, spatial multiplexing, adaptive modulation and Non-Orthogonal Multiple Access (NOMA). Adaptive Modulation makes use of the user's location from his base station, such that, closer users get bigger constellation size and hence higher data rate. A similar idea of adaptive modulation that makes use of the user's locations is the NOMA technique. Here the base station transmits composite signals each for a different user at a different distance from the base station. The transmitted signal is formed by summing different user's constellations with different weights. The closer the users the less average power constellation is used. This will allow the closer user to the base station to distinguish his constellation and others constellation. The far user will only distinguish his constellation and other user's data will appear as a small interference added to his signal. In this paper, it is shown that the Adaptive modulation and the NOMA are special cases of the more general Cluster Modulation technique. Therefore, a general frame can be set to design both modulation schemes and better understanding is achieved. This leads to designing a multi-level NOMA and/or flexible adaptive modulation with combined channel coding.

Keywords

Cluster Modulation, Adaptive Modulation, NOMA

1. Introduction

Current and future systems become more bandwidth demanding, since the most popular applications are multimedia communications. As well as the introduction of massive Wireless Sensor Networks arises the challenge for the communication systems capacity increase. This leads to the use of very sophisticated signal processing techniques that require good processing cores to be employed in the communications devices.

The need for more transmission data rate or higher systems capacity led to several solutions including higher constellation size, spatial multiplexing, adaptive modulation and Non-Orthogonal Multiple Access (NOMA). Increasing the constellation size requires more power to compensate for the loss in SNR that maintains acceptable BER. Error control coding might be utilized to enhance the BER on the expenses of higher Band Width (BW). Spatial multiplexing implements orthogonal channels in space that can be used to transmit different user's data at each beam using an antenna array. Space Time Codes might be implemented to form spatially multiplexed channels. This will increase the system's capacity by reusing the same bandwidth many times in the same cell. Adaptive Modulation makes use of the user's location from his base station, such that, closer users get bigger constellation size and hence higher data rate. A similar idea of adaptive modulation that makes use of the user's locations is the NOMA technique. Here the base station transmits composite signals each for a different user at a different distance from the base station. The transmitted signal is formed by summing different user's constellations with different weights. The closer the users the less average power constellation is used. This will allow the closer user to the base station to distinguish his constellation and others constellation. The far user will only distinguish his constellation and other user's data will appear as a small interference added to his signal. With NOMA, multiple users share the same radio resources, either in time, frequency or code. It is well-known that non-orthogonal user multiplexing using superposition at the transmitter and Successive Interference Cancellation (SIC) at the receiver outperforms orthogonal multiplexing and it is optimal in the sense of achieving the capacity region [1] [2]. NOMA captures researcher's attention as a novel and promising multiple-access scheme for future generations of cellular systems as well as for Wireless Sensor Networks (WSN) [3]-[9]. **Figure 1** shows the concept of NOMA for two users, one U1 is close to base station and the second U2 is far from base station.

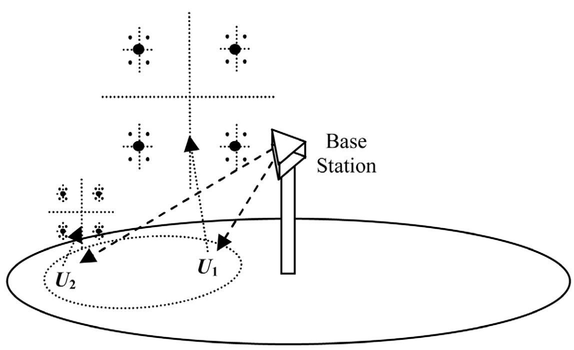

Figure 1. Two users NOMA system showing their constellations.

As shown in **Figure 1**, the first user can detect both his data and the second user's data. The second user sees the first user's data as interference and is still capable of detecting his own data.

In 1996 a Ph.D. thesis introduced the concept of what was called Cluster Modulation (CM). In CM many levels of constellation are superimposed to form the total transmitted signal from the base station. Higher levels may be used for transmitting side information data to the basic level. The extended levels can also be used to increase the data rate for the same user or use different user data. When CM is used to increase the data rate, it becomes similar to the Adaptive Modulation scheme and when used to transmit different user's data it becomes similar to the NOMA technique [10]-[13]. The block diagram of the CM transmitter is shown in **Figure 2**. Here the transmitted signal for L levels QAM constellation can be written as:

$$\Phi_t(t)=\sum_{l=0}^{L-1}\alpha_l s_l(t) \tag{1}$$

where α_l is the lth level weight and $s_l(t)$ is the complex lth user signal that represents a constellation point. And for PSK constellation:

$$\Phi_t(t)=\sum_{l=0}^{L-1}\alpha_l s_l(t) \tag{2}$$

where $p(t)$ is the waveform shaping function.

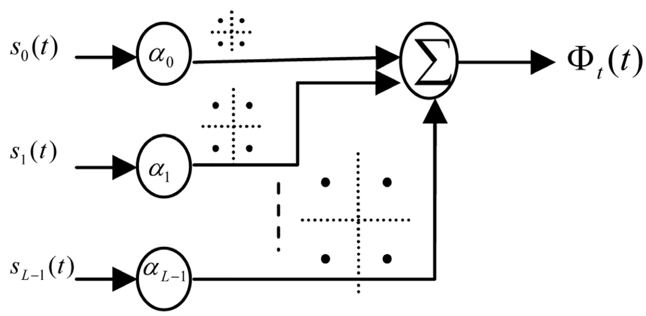

Figure 2. CM transmitter block diagram with example of 4-QAM constellation.

The resulting constellation of $\Phi_t(t)$ will be a superposition of all levels. An example of L = 3 4 QAM signals is shown in **Figure 3**. Generally, the signals $s_l(t)$'s can have arbitrary different constellations.

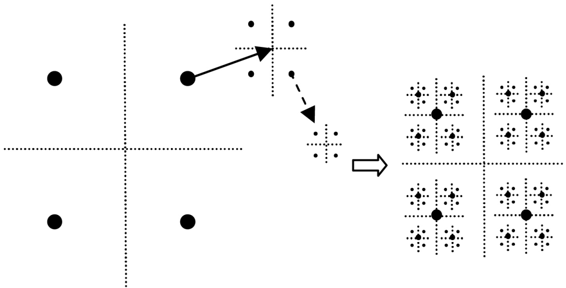

Figure 3. Three levels CM Constellation QAM.

$s_l(t)$ can be different users signal or same user data. L is the number of levels used that can be fixed or variable. The weight factors α_l's usually have the following constraint:

$$\alpha_0 < \alpha_1 < \cdots < \alpha_{L-1} \tag{3}$$

In case of PSK modulation for each level, the weight factors α_l's will scale the transmitted signal phases at each level. Then the constellation will be as in Figure 4.

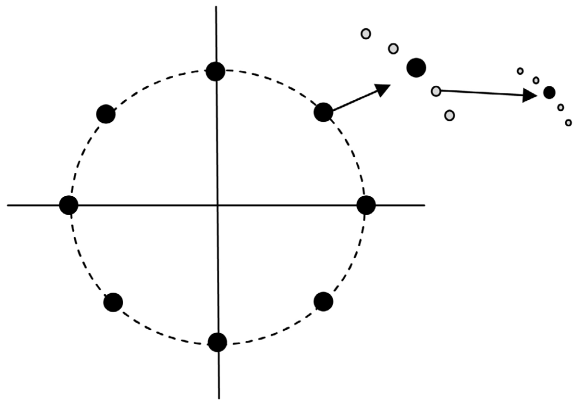

Figure 4. Three levels CM constellation PSK.

The CM receiver is a sequential receiver that detects the signals from the low level up to the highest level, as shown in Figure 5.

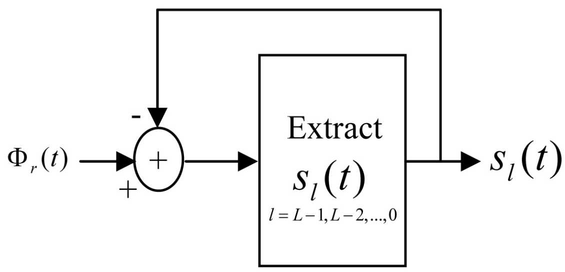

Figure 5. CM receiver block diagram.

The Extractor function is to detect the signal $s_l(t)$ using its own constellation in descending order ($l = L-1, L-2, \cdots, 0$). This is done by mapping all the decision regions of the lower level into one constellation of the next level until reaching the highest level and detecting the data backward. In this paper we formulate the relation between the CM and Adaptive modulation and then between the CM and NOMA.

2. CM Leading to Adaptive Modulation

Adaptive Modulation is used to provide different data rates to users as their distance from the base station. Users will get constellation size depending on their distance from base station, such that, the distance is divided into zones. Each zone will use power of 2 size reduction from the previous zone [14]-[20]. If we consider the four zones system, then the closest zone will have 64-ary constellation, the next zone will have 16-ary constellation then 4-ary and the farthest one will have binary constellation as shown in Figure 6. This will result in higher data rates for the closer zones.

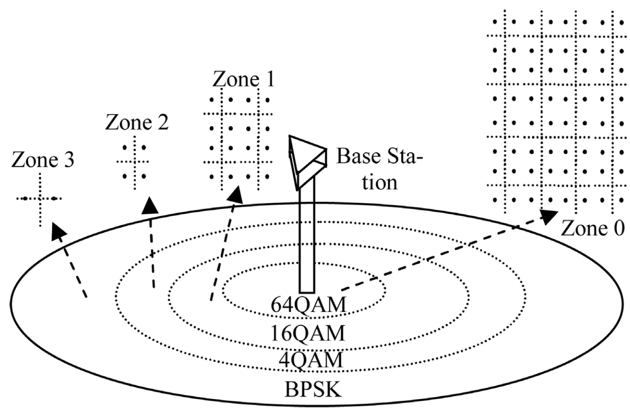

Figure 6. Four zones adaptive modulation scheme.

For L level CM, users at distance r_l from base station (r_0 is the closest). The transmitted signal to zone 0 will use all the L levels for the same user. The next zone will use L-1 levels CM and so on. In each zone we use a complete CM constellation for the same user and if we set the following constraint, we will get exact constellation for both the CM and the Adaptive Modulation scheme.

$$\alpha_l = \frac{\alpha_{l+1}}{2}, l = 0,1,2,\cdots,L-2 \tag{4}$$

As shown in Figure 6 the constellation for both Adaptive Modulation and 4 levels CM is identical (that is used in the closest zone). Here the CM technique can be used to generate any level of constellation size in the same way as the Adaptive Modulation and hence, the same receiver can be used to retrieve the data for all zones. In the case of CM, the transmitter will divide the user data into sub-groups of bits each sub-group is fed to a different level. In the case of 64-ary constellation we need three levels CM to form the constellation points that is three 2-bits sub-groups; this will be used in the closest zone to base station. And in the next zone we use two levels CM to form the 16-ary constellation and in the next zone one CM level with 4-ary constellation is needed finally in the last zone one level CM with a binary constellation is needed.

The CM can form the Adaptive modulation scheme, but it does not cover the adaptation process, since it only describes the constellation design and implementation. The CM provides a flexible method to control the power for each level individually by controlling the values of α_l's for each zone and even for each level. This will result in an unequal error protection scheme that can have better BER performance for the more important data. A comparison between 16-ary constellations for both equal and unequal error protection is shown in Figure 7.

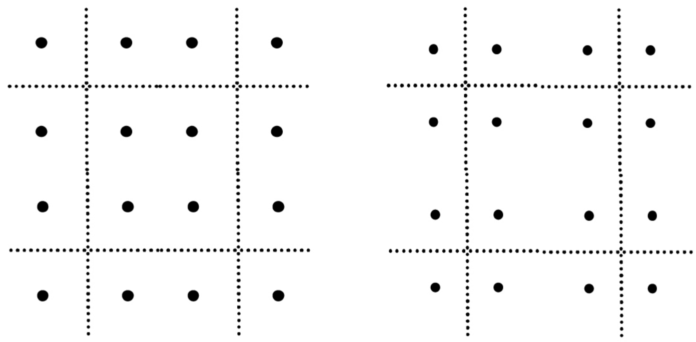

Figure 7. 16-ary constellation for equal error protection (left) and unequal error protection (right).

In this example we can see that the Euclidean distance between constellation points in level 0 is less than the Euclidean distance between constellation points in level 1. This can be written as:

$$\alpha_0 = \frac{\alpha_1}{p} \quad \text{where} \quad p \geq 2 \tag{5}$$

where p is a constant that specifies the amount of reduction in the Euclidean distance between the constellation points. If we have more than two levels Equation (4) becomes:

$$\alpha_l = \frac{\alpha_{l+1}}{p_l}, l = 0,1,2,\cdots,L-2 \quad \text{and} \quad p_l \geq 2 \tag{6}$$

As discussed above, the CM leads to designing the same constellation used in the Adaptive Modulation and provides more flexibility to implement Unequal Error protection scheme. The adaptation can be introduced simply by controlling the P_l and α_l factors. Next, we discuss the relation between the CM and the NOMA.

3. CM Leading to NOMA

The introduction of NOMA in the 5G systems has the impact of increasing the overall systems capacity [21]-[26]. This increases the importance of using NOMA systems in current and future communications systems. For users at distance r_l from base station where:

$$r_0 < r_1 < \cdots < r_{L-1} \tag{7}$$

It is assumed that the closer users have higher SNR than the far users. Therefore, Equations (1) and (6) can represent generalized NOMA constellation. For example, in 2 levels CM the transmitted signal with $\alpha_0 = \frac{\alpha_1}{2} = 1$ and 4-QAM constellation for each level, the transmitted signal can be written as:

$$\Phi_t(t) = s_0(t) + 2s_1(t) \tag{8}$$

where $s_0(t)$ and $s_1(t) \in \{1+j,-1+j,1-j,-1-j\}$, This will produce constellation points as shown in Figure 8. The same constellation can be seen as a

NOMA with two users the close user data corresponding to level 0 and the far user data corresponding to level 1.

At the receiver assuming AWGN channel for simplicity, the received signal is given by:

$$\Phi_r(t) = s_0(t) + 2s_1(t) + n(t) \tag{9}$$

$n(t)$ is AWGN. Here the receiver will detect level 1 signal first and will subtract it from the whole signal and then detect level 0 signal.

In general, the receiver will be a successive cancellation receiver. Starting at the higher level and going down to the lower levels. Each time it will subtract the lower level from the previous signal to detect the next level.

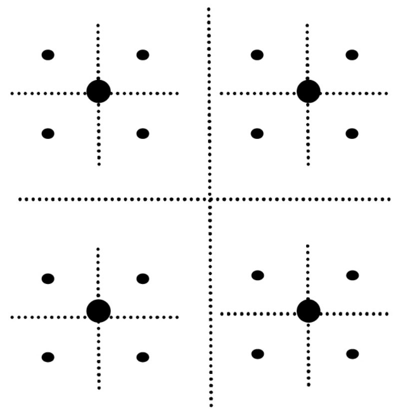

Figure 8. Example of two levels CM with $p_0 = 2$.

In CM, the extended levels might use simple repetition code to enhance their SNR such that each level l can repeat its data along q_l successive signaling intervals. Figure 9 shows an example of two levels CM scheme with $q_0 = 2$ where we repeat twice level 0 data.

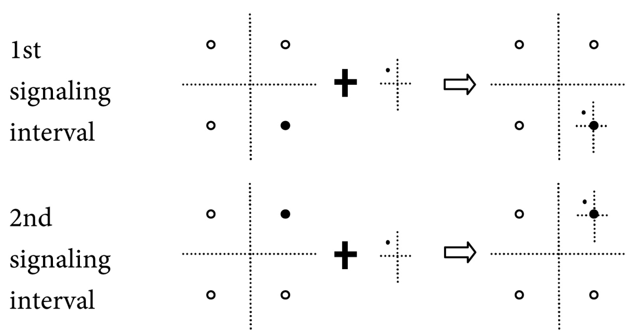

Figure 9. Example of two levels CM with $p_0 = 3$ and $q_0 = 2$.

The repetition code can be replaced by any error correcting code to get better performance for each level to form a Coded Modulation scheme. In the shown example the close user will detect his data as:

$$I_0 = \text{Abs}\left(\text{Re}\left\{\Phi_r\left(t\right)\right\}\right) - \alpha_1 \text{ and } Q_0 = \text{Abs}\left(\text{Im}\left\{\Phi_r\left(t\right)\right\}\right) - \alpha_1 \tag{10}$$

And then detecting the other level as:

$$I_1 = \text{Re}\left\{\Phi_r\left(t\right)\right\} - I_0 \text{ and } Q_1 = \text{Im}\left\{\Phi_r\left(t\right)\right\} - Q_0 \tag{11}$$

We can see that the CM can be a more generalized form of NOMA as well as it can combine coding techniques to enhance the receiving performance.

4. Performance

A MatLab simulation was conducted with an average of 2 million iterations at each SNR value for both Adaptive Modulation and NOMA using 4-ary QAM for each zone and compared with CM with two levels and no repetition code with the same constellation size.

The CM performance in AWGN channel matches the performance of adaptive modulation when it uses the right parameters (*i.e.* for 2-levels adaptive modulation set: $L = 3$ and $p = 2$). Here, both the adaptive modulation and the CM matches exactly and hence, there BER performance coincide as shown from MatLab simulation in **Figure 10**.

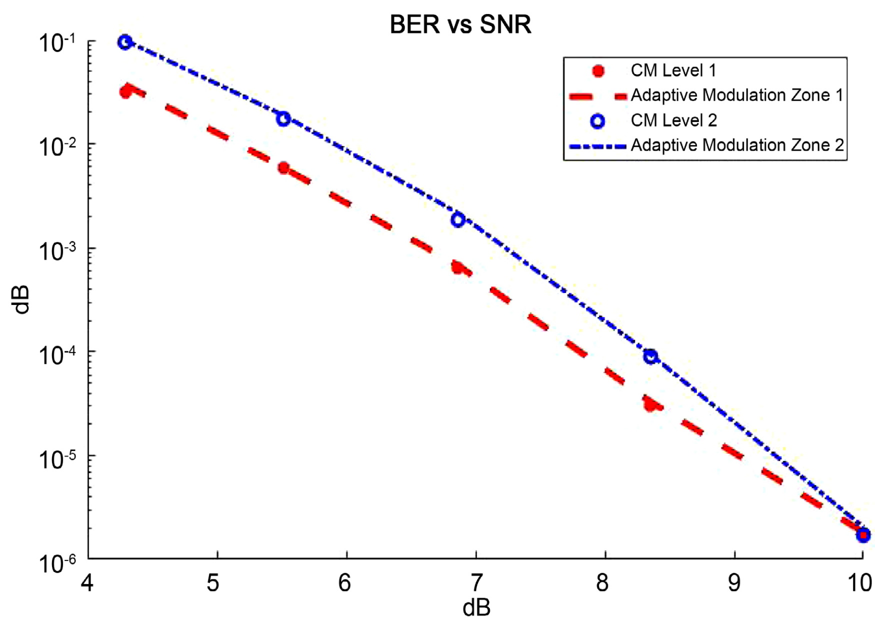

Figure 10. CM and Adaptive modulation performance for the same parameters.

Again, the CM performance in AWGN channel matches the performance of NOMA when it uses the right parameters (*i.e.* $p_0 = 2$ and $q_0 = 1$). Here, both the NOMA and the CM matches exactly and hence, there BER performance coincide as shown from MatLab simulation in **Figure 11**.

As shown the BER performance in AWGN channel in both cases matches their counterpart. The CM has the advantage of combining a repetitive code to further enhance the higher levels data. This can be done by setting $q_0 > 1$.

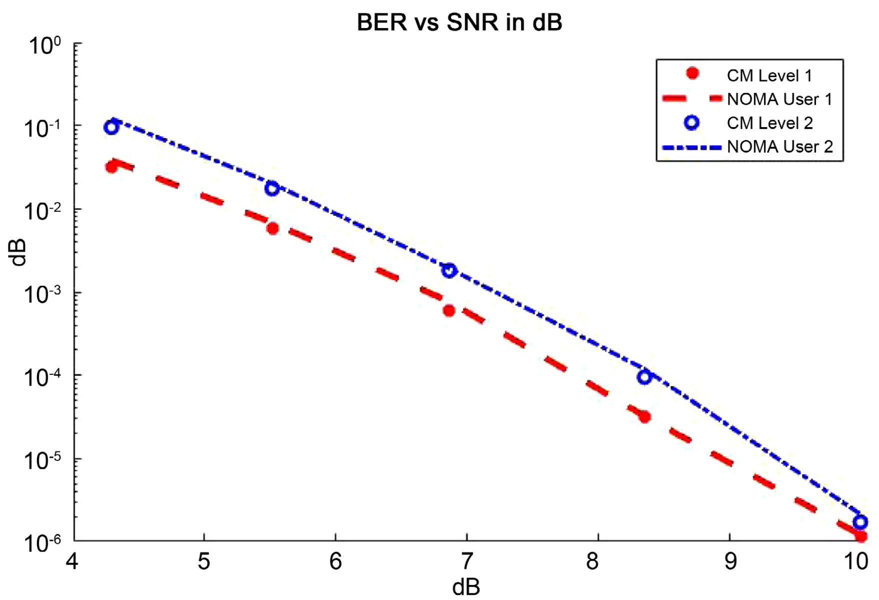

Figure 11. CM and NOMA performance for the same parameters.

5. Conclusion

In this paper, it is shown that the CM is a generalized modulation form that can represent adaptive modulation as well as NOMA. The CM BER performance also matches the similar adaptive modulation and NOMA constellations. The CM can also use any type of constellation to represent a multi-user modulation scheme. The CM can be implemented as an unequal error protection scheme as well as it can combine coding with modulation to further protect the different levels independently.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Tse, D. and Viswanath, P. (2005) Fundamentals of Wireless Communication. Cambridge University Press. https://doi.org/10.1017/cbo9780511807213

[2] Caire, G. and Shamai, S. (2003) On the Achievable Throughput of a Multiantenna Gaussian Broadcast Channel. *IEEE Transactions on Information Theory*, **49**, 1691-1706. https://doi.org/10.1109/tit.2003.813523

[3] Higuchi, K. and Kishiyama, Y. (2012) Non-Orthogonal Access with Successive Interference Cancellation for Future Radio Access. APWCS.

[4] Endo, Y., Kishiyama, Y. and Higuchi, K. (2012) Uplink Non-Orthogonal Access with MMSE-SIC in the Presence of Inter-Cell Interference. 2012 *International Symposium on Wireless Communication Systems* (*ISWCS*), Paris, 28-31 August 2012, 261-265. https://doi.org/10.1109/iswcs.2012.6328370

[5] Benjebbour, A., Saito, Y., Kishiyama, Y., Li, A., Harada, A. and Nakamura, T. (2013) Concept and Practical Considerations of Non-Orthogonal Multiple Access

(NOMA) for Future Radio Access. 2013 *International Symposium on Intelligent Signal Processing and Communication Systems*, Naha, 12-15 November 2013, 770-774. https://doi.org/10.1109/ispacs.2013.6704653

[6] Saito, Y., Benjebbour, A., Kishiyama, Y. and Nakamura, T. (2013) System-Level Performance Evaluation of Downlink Non-Orthogonal Multiple Access (NOMA). 2013 *IEEE* 24*th Annual International Symposium on Personal*, *Indoor*, *and Mobile Radio Communications* (*PIMRC*), London, 8-11 September 2013, 611-615. https://doi.org/10.1109/pimrc.2013.6666209

[7] Benjebbour, A., Anxin Li,, Saito, Y., Kishiyama, Y., Harada, A. and Nakamura, T. (2013) System-Level Performance of Downlink NOMA for Future LTE Enhancements. 2013 *IEEE Globecom Workshops* (*GC Wkshps*), Atlanta, 9-13 December 2013, 66-70. https://doi.org/10.1109/glocomw.2013.6824963

[8] Higuchi, K. and Kishiyama, Y. (2013) Non-Orthogonal Access with Random Beamforming and Intra-Beam SIC for Cellular MIMO Downlink. 2013 *IEEE* 78*th Vehicular Technology Conference* (*VTC Fall*), Las Vegas, 2-5 September 2013, 1-5. https://doi.org/10.1109/vtcfall.2013.6692307

[9] Li, A., Benjebbour, A. and Harada, A. (2014) Performance Evaluation of Non-Orthogonal Multiple Access Combined with Opportunistic Beamforming. 2014 *IEEE* 79*th Vehicular Technology Conference* (*VTC Spring*), Seoul, 18-21 May 2014, 1-5. https://doi.org/10.1109/vtcspring.2014.7023050

[10] Higuchi, K. and Benjebbour, A. (2015) Non-Orthogonal Multiple Access (NOMA) with Successive Interference Cancellation for Future Radio Access. *IEICE Transactions on Communications*, **98**, 403-414. https://doi.org/10.1587/transcom.e98.b.403

[11] Rahhal, J. (1996) Cluster Modulation for Power/Bandwidth Efficient Communication. Ph.D. Thesis, Illinois Institute of Technology.

[12] Rahhal, J., Patel, B. and Atkin, G.E. (1994) Clustered Modulation for Bandwidth Efficient Transmission of Side Information. *International Conference on Communication Technology* (*ICCT*'94), Shanghai, 8-10 June 1994, 1121-1126.

[13] Rahhal, J. and Atkin, G.E. (1997) Cluster Modulation: A Constellation Expansion Technique for Bandwidth Efficient Communication. *IEEE Symposium on Advances in Computers and Communications*, Alexandria, 27-29 June 1997.

[14] Rahhal, J., Wang, Y.-L. and Atkin, G.E. (1997) PSK-Based Constellation Expansion for Fading Multipath Channels. 2*nd IEEE Symposium on Computers and Communications*, Alexandria, 1-3 July 1997, 685-689.

[15] Abdelaziz, M. and Gulliver, T.A. (2018) Triangular Constellations for Adaptive Modulation. *IEEE Transactions on Communications*, **66**, 756-766. https://doi.org/10.1109/tcomm.2017.2762671

[16] Wang, Y., Liu, W. and Fang, L. (2020) Adaptive Modulation and Coding Technology in 5G System. 2020 *International Wireless Communications and Mobile Computing* (*IWCMC*), Limassol, 15-19 June 2020, 159-164. https://doi.org/10.1109/iwcmc48107.2020.9148457

[17] Kojima, S., Maruta, K. and Ahn, C. (2019) Adaptive Modulation and Coding Using Neural Network Based SNR Estimation. *IEEE Access*, **7**, 183545-183553. https://doi.org/10.1109/access.2019.2946973

[18] Yaghubi-Namaad, M., Rahbar, A.G. and Alizadeh, B. (2018) Adaptive Modulation and Flexible Resource Allocation in Space-Division-Multiplexed Elastic Optical Networks. *Journal of Optical Communications and Networking*, **10**, 240-251. https://doi.org/10.1364/jocn.10.000240

[19] Abu-Baker, A., Alshamali, A. and Shawaheen, Y. (2021) Energy-Efficient Clus-

ter-Based Wireless Sensor Networks Using Adaptive Modulation: Performance Analysis. *IEEE Access*, **9**, 141766-141777. https://doi.org/10.1109/access.2021.3118672

[20] Boulogeorgos, A.A., Papasotiriou, E.N. and Alexiou, A. (2018) A Distance and Bandwidth Dependent Adaptive Modulation Scheme for THz Communications. 2018 *IEEE 19th International Workshop on Signal Processing Advances in Wireless Communications* (*SPAWC*), Kalamata, 25-28 June 2018, 1-5. https://doi.org/10.1109/spawc.2018.8445864

[21] Shanthi, K.G. and Manikandan, A. (2019) An Improved Adaptive Modulation and Coding for Cross Layer Design in Wireless Networks. *Wireless Personal Communications*, **108**, 1009-1020. https://doi.org/10.1007/s11277-019-06448-1

[22] Benjebbour, A., Saito, K., Li, A., Kishiyama, Y. and Nakamura, T. (2015) Non-Orthogonal Multiple Access (NOMA): Concept, Performance Evaluation and Experimental Trials. 2015 *International Conference on Wireless Networks and Mobile Communications* (*WINCOM*), Marrakech, 20-23 October 2015, 1-6. https://doi.org/10.1109/wincom.2015.7381343

[23] Akbar, A., Jangsher, S. and Bhatti, F.A. (2021) NOMA and 5G Emerging Technologies: A Survey on Issues and Solution Techniques. *Computer Networks*, **190**, Article ID: 107950. https://doi.org/10.1016/j.comnet.2021.107950

[24] Kumar, A., Kumar, K., Gupta, M.S. and Kumar, S. (2020) A Survey on NOMA Techniques for 5G Scenario. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3573579

[25] Zaman, N.U., Hassan, A.K., Abbas, Z.H., Abbas, G., Bilal, M. and Pack, S. (2023) Performance Analysis of NOMA Enabled Multi-User Co-Operative IoT Network with SWIPT Protocol. *Journal of King Saud University-Computer and Information Sciences*, **35**, Article ID: 101639. https://doi.org/10.1016/j.jksuci.2023.101639

[26] Mounir, M., El_Mashade, M.B. and Mohamed Aboshosha, A. (2021) On the Selection of Power Allocation Strategy in Power Domain Non-Orthogonal Multiple Access (PD-NOMA) for 6G and Beyond. *Transactions on Emerging Telecommunications Technologies*, **33**, e4289. https://doi.org/10.1002/ett.4289