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Evolution of multiple-access networks — cellular and non-cellular — in historical perspective. Part 4

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Introduction: *The goal of this issue is the analysis of evolution of the current and novel wireless networks, from second generation (2G) to fifth generation (5G), as well as changes in technologies and their corresponding theoretical background and protocols — from Bluetooth, WLAN, WiFi and WiMAX to LTE, OFDM/OFDMA, MIMO and LTE/MIMO advanced technologies with new hierarchy of cellular maps design — femto/pico/micro/macro.* ***Methods:*** *We use new theoretical frameworks for description of the advanced technologies, such as multicarrier diversity technique, OFDM and OFDM novel approach, MIMO aspects description based on multi-beam antennas approach, various cellular maps design based on a new algorithms of femto/pico/micro/macrocell deployment, and a new methodology of a new MIMO/LTE system integration based on multi-beam antennas.* ***Results:*** *We have created a new methodology of multi-carrier diversity description for novel multiple-access networks, of usage of OFDM/OFDMA modulation to obey inter-user and inter-symbol interference in multiple-access networks, of how to obey the multiplicative noises occurring in the multiple-access wireless networks, caused by multi-ray phenomena, and finally, of how to overcome propagation effects occurring in the terrestrial communication links by use combination of MIMO and LTE technologies based on multi-beam antennas. For these purposes we present new stochastic approach that accounts for the terrain features, such as buildings' overlay profile, buildings' density around the base station and each user antennas, and so forth. These parameters allow us to estimate for each situation occurs at the built-up terrain area the effects of fading, as a source of multiplicative noise.* ***Practical relevance:*** *New methodology of how to estimate effects of multiplicative noise, inter-user and inter-symbol interference, occurring in the terrestrial wireless networks, allows us to predict a-priory practical aspects of the current and new multiple-access wireless communication networks, such as: the users' capacity and user's links spectral efficiency for various configurations of cells deployment — femto, pico, micro, and macro, as well as the novel MIMO/LTE system configuration for future networks of 4th and 5th generation deployment.*

Keywords *— network capacity, LTE releases, multiple-input-multiple-output, MIMO, multiple user, MU, single-input-single-output, SISO, single-input-multiple-output, SIMO, single carrier, SC, single user, SU, spectral efficiency, user equipment, UE, wireless fidelity network, WiFi, wireless metropolitan area network, WiMAX.*

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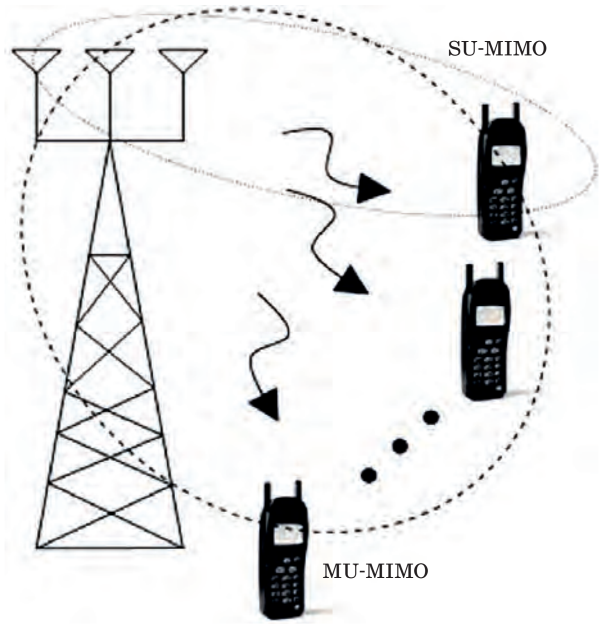
Start in *Informatsionno-upravliaiushchie sistemy* [Information and Control Systems], 2018, no. 4, pp. 86–104, doi:10.31799/1684-8853-2018-4-86-104; 2018, no. 5, pp. 94–103, doi:10.31799/1684-8853-2018-5-94-103; 2018, no. 6, pp. 82–94, doi:10.31799/1684-8853-2018-6-82-94

SU/MU MIMO technology embedded into LTE network

However, even using a single-carrier (SC) or single-user (SU) FDMA modulation technique for uplink transmission and a SC-OFDMA technique for downlink transmissions (see definitions in [147]), it is difficult to provide a wide range of spectra allocations of different sizes for each subscriber located in various terrestrial conditions, as well as a significant increase in spectrum efficiency compared to previous 2G and 3G cellular networks. This can be achieved only by combining Advanced FDMA and OFDMA technologies with MIMO systems performed on the basis of multi-beam or phased-array antennas [135–143]. The LTE Release 8 was recently expanded from two to 4 antennas in downlink spatial multiplexing from a BS, as shown in Fig. 26 (called also SIMO (single-input-multiple-output)-LTE system).

Here, the layers can be defined as simultaneously transmitted streams of data to multiple UEs using the same time-frequency resource. In such a manner, any transmission of separate data streams is distributed among desired layers. The pre-coder matrix indicator (or selection suggestion matrix) is needed to transfer the selected data for each desired user (see details in reference [143]). The LTE Release 9, as a new dual-layer transmission mode, also was performed for supporting of up to 4 transmitted antennas at the BS in downlink channel.

Now we postulate the following question: if both LTE Releases 8 and 9 could be integrated with MIMO, can such a combined LTE-MIMO system satisfy the International Mobile Telephony (IMT) requirements. Table 2 presents a comparative anal-



■ ***Fig. 26.*** Geometrical configuration of SU-MIMO and MU (multiple user)-MIMO in integrated LTE-MIMO system

■ ***Table 2.*** Requirements of IMT-Advanced (LTE Release 10) vs. LTE Release 8 system (extracted from Internet)

		IMT-Advanced requirement	LTE Release 8
Transmission bandwidth, MHz	—	At least 40	Up to 20
Peak spectral efficiency, bps/Hz	DL	15	16
	UL	6.75	4
Latency, ms	Control plane	Less than 100	50
	User plane	Less than 10	4.9

ysis of these requirements with respect to those that satisfy the deployments of LTE Release 8 system. It is clear seen that, even giving better latency for each UE, but using twice-narrower bandwidth, Release 8 cannot support high-rate transmission of data streams for each individual user. A fully-adaptive MU-MIMO transmission mode cannot be realized in cooperation with LTE Release 8 and LTE Release 9 [132, 133, 142, 144].

Recently, a new MU-MIMO antenna system was introduced called the Advanced LTE (A-LTE) or, simply, LTE Release 10 [140–142]. We will introduce this advanced technology since, as was mentioned in references [145], it is better equipped to meet the requirements of the modern 4th generation of wireless networks.

As seen in Fig. 27, the LTE Release 10, or A-LTE, can use at BS with at least 8 separate antennas for downlink MU connections, whereas for uplink, up to 4 UE antennas can be utilized. Here, a layer mapping supports the transfer of individual codes from 2 codebooks to each pre-decoding layer.

At the MU terminals, a de-mapping layer is used for transporting to each individual user its desired data codes. The use of a MIMO system at both end terminals allows for:

— fast user channel estimation, selecting and equalization;

— reliable cancellation of MU interference;

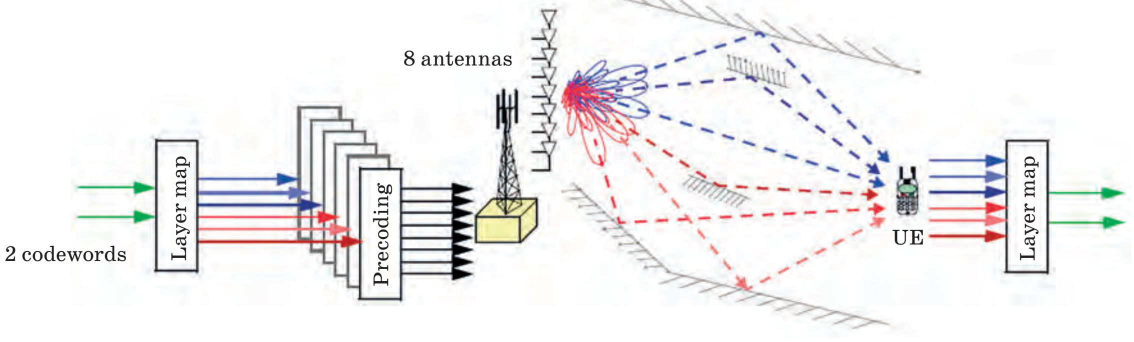
— simplification of complexity of the interference-aware receiver;

— reduction of the system's detection complexity;

— fitting of each single antenna of UEs in MIMO configuration;

— better implementation in the existing hardware, and so on.

In works [134, 143, 145] were introduced the scheduling algorithms, based on the geometrical alignment at the BS, which can minimize the IUI seen by each UE. In such a configuration, the proposed interference-aware receiver was found as a



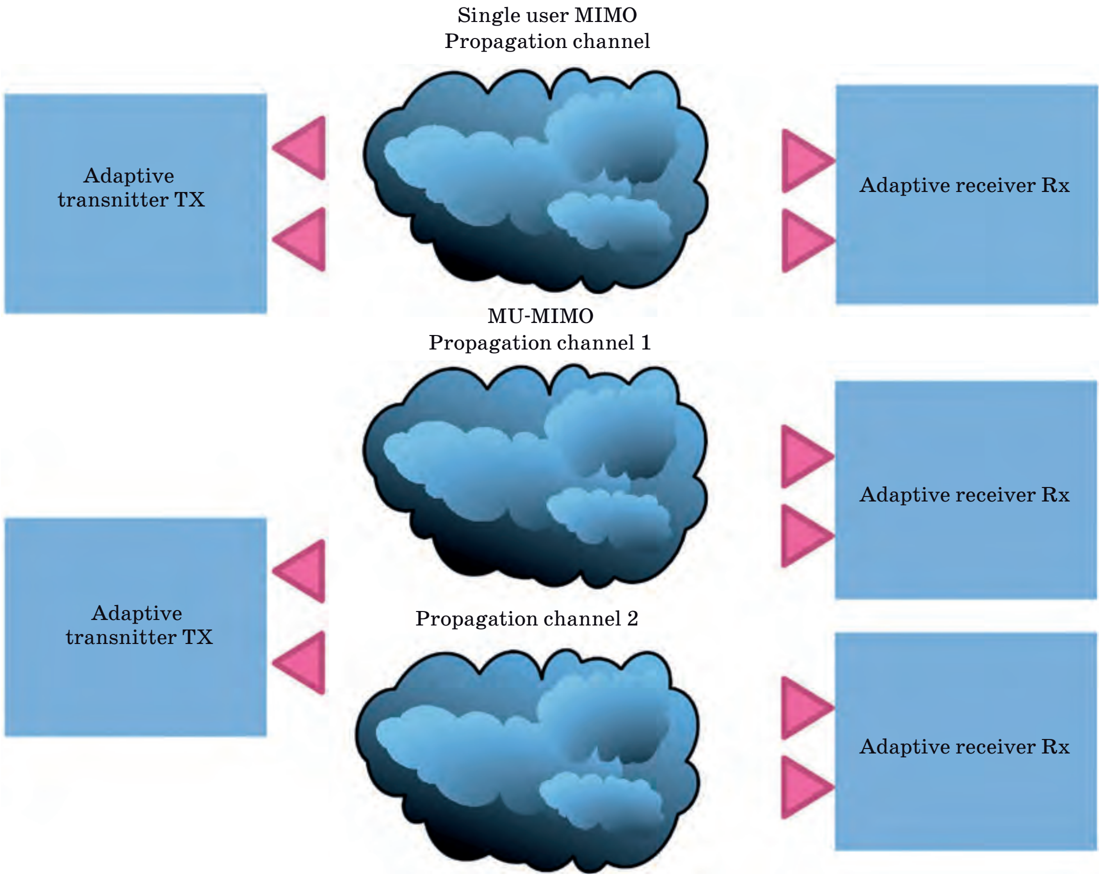
■ ***Fig. 27.*** Downlink transmission from BS arranged by 8 antennas to UEs in MIMO-LTE integrated network (rearranged from [131, 140, 141]) good candidate for the practical implementation in MU-MIMO LTE Release 10 combined system.

To show the difference between the SU-SISO (single user single-input-single-output), MU-MIMO systems and the latter based on multi-beam antennas, we schematically presented them in Fig. 28. The first system is based on point-to-point single BS and single UE antennas, whereas the second one is based on multiple antennas from both side terminals [146].

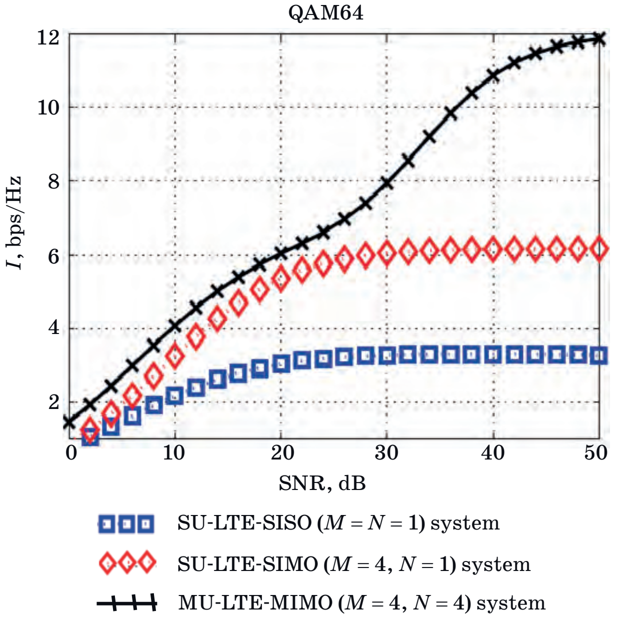
To show the efficiency of usage of combination of MIMO/LTE network based on multi-beam antennas with respect to SISO network, we present the computations of a normalized maximum sum rate I [in bits/s/Hz] of downlink based on the mathematical algorithm fully described in [146]. In simulations, we account for a SU-SISO (that is, for $M = 1$, $N = 1$), for a SU-SIMO (single user single-input-multiple-output) (that is, for $M = 1$, $N = 4$), and for a MU-MIMO (that is, for $M = 4$, $N = 4$) integrated schemes (in the case of antenna correlated elements). The results of the numerical experiment are shown in Fig. 29.

It is clear seen from the presented illustrations that using the MU-MIMO system of various input-output antenna elements integrated as an example, with an Advanced LTE technology, it is possible to increase the spectral efficiency and the data rate in such an integrated MU-MIMO network. Moreover, both SU-SIMO (or MISO) LTE and MU-MIMO LTE integrated systems, with a high correlation between transmitter and receiver multi-beam antennas (Fig. 30), show better performance in spectral efficiency and data stream rate [146]. Thus, it can be seen that the LTE-SU Rx gives low spectral efficiency and data rate with respect to the MU-MIMO A-LTE system. The later has a tendency to increase spectral efficiency and data rate per several times with respect to the previous systems and this tendency increases with an increase in SNR. With increase of amount of UE antennas and BS antennas this difference becomes more significant.

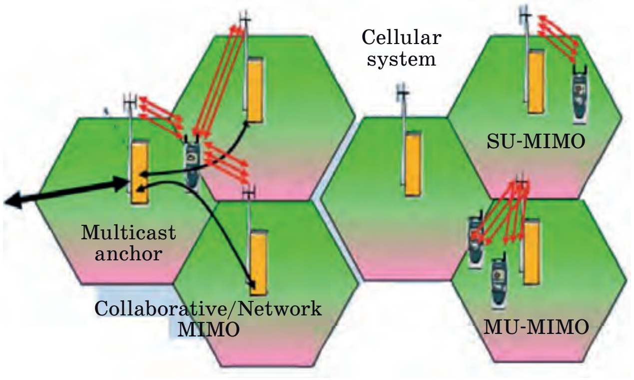
Finishing this paragraph, we should outline that by controlling of number of elements of multi-beam antennas at the both end terminals, BS and UEs, and *a priory* accounting for the real responses of each channel on multipath fading phenomena (by prediction of the real K-factor of fading) [148], we show the same effects, as were obtained in [140, 142–145], where a set of precoding codebooks (from one to several) was introduces for extension of the LTE Releases 8 to 10, using MIMO configurations with 2 or 4 transmitting antennas, or a dual-code-



■ ***Fig. 28.*** Single user SISO network (top panel) and multiple user MIMO network (bottom panel)



■ ***Fig. 29.*** Spectral efficiency (extracted from [146] with the same notations, as done in [134])



■ ***Fig. 30.*** The proposed implementation of cellular, LTE and SU/MU-MIMO systems into the integrated configuration of future 4th generation network

book deployment [134] for MIMO configuration with 8 transmitting antennas at the BS terminal. What is important to notice is that the main limiting factors that can decrease efficiency of the proposed MIMO system integrated, for example, with the Advanced LTE Releases from 8 to 10, observed during numerical computations based on the real experiment carried in built-up area, are the *K*-factor of fading, as a response of each individual communication channel on data transmission, and number of antenna beams within each terminal of the system, BS and UE.

Despite the fact that the approaches, proposed in [134, 140, 142–145] can significantly reduce a total LTE/MIMO system structure yielding a low-complexity of signal processing against inter-user interference, as was shown in [146], without accounting for derivation of the *K*-factor based on various topographic scenarios of the built-up areas of service, as well as for the effective configuration of MIMO system based on multi-beam antennas [146], it is impossible a priory predict data stream parameters and efficiency of each specific propagation channel “hidden” in the whole system, based on strict analysis of the channel response, and, finally, increase efficiency of the proposed Advanced LTE/MIMO-R10 network by managing and control of its GoS and QoS.

■ ***Fig. 31.*** LTE-MIMO network configuration based on multi-beam antennas

Finally, following results obtained in references [135–146], as well as the recommendations stated there, we present the reader the following configuration of the SU-MIMO and MU-MIMO integrated with Advanced LTE, “hidden” into the conventional cellular-map scheme, as is shown in Fig. 31.

Such configurations can be extended for the combined femtocell/picocell/microcell/macrocell planning tool design (see Fig. 31).

These schemes can be considered as a best candidate of the convenient configurations that satisfied requirements of the 4th and 5th generation networks.

Summary

In Section 1, we introduced the reader into the conventional and current techniques, technologies and systems adapted for 2nd (2G) and 3rd (3G) generations of wireless networks, as well as the advanced technologies and their corresponding protocols used to utilize modern networks beyond 3G, such as 4th and 5th generations. A new generations, called 4th (4G) and 5th (5G), were introduced, which are ex-

■ ***Table 3.*** IMT requirements for 4th generation vs. the last LTE Releases and WiMAX 1st and 2nd generations of networks

		IMT-Advanced requirement	LTE Release 8	LTE Release 10	Wimax 1.0	Wimax 2.0
Transmission Bandwidth, MHz	—	At least 40	Up to 20	Up to 100	Up to 10	Up to 40
Peak spectral Efficiency, bps/Hz	DL	15	16	16	6.4	15
	UL	6.75	4	8.1	2.8	6.75
Latency, ms	Control plane	< 100	50	50	50	30
	User plane	< 10	4.9	4.9	20	10

pected to be capable of providing wider bandwidth, higher data stream rates, greater interoperability accords various communication protocols, without any collusion between them, user's security and non-collision communications between users, that is, to provide significant increase in GoS and QoS.

Thus, typical 2G standards as GSM (Global System for Mobile Communications) operated at 900 to 1900 MHz frequency band, which used TDMA/FDMA separate or combined digital modulation techniques, have not satisfied the high-data communication requirement. The Universal Mobile Telecommunications Systems (UMTS) standards that were related to 2.5G and 3G mobile systems, dealt with higher voice capacity and higher-speed digital data. The same parameters were expected for 3G communication networks such as WPAN (or Bluetooth), WiFi (or WLAN), WiMAX; all described briefly above. Unfortunately, even integrating and combined the existing 2G and 3G networks, technologies and protocols, was problematic to achieve 200 Mbps–1 Gbps data rate, multimedia (video and audio) applications, as well as terminal's heterogeneity related to significant decrease of the network costs, greater mobile signal availability in a "jungle of noises" caused by multipath fading.

For these reasons in the 4th and 5th generations, a physical layer was significantly broadened by serving a wide range of frequency bands (see Sections 2 and 3).

In our opinion, recently performed modern LTE and LTE-A networks integrated with MIMO systems based on multi-antenna (multi-beam or phased-array) technology, briefly described in Sections 4, can substantially improve 4G network spectrum efficiency providing three kind of advantages with respect to single antenna LTE system:

— transmit time diversity;

— beamforming;

— spatial multiplexing.

All these advantages are shown in Table 3. Moreover, using spatial multiplexing, the number of simultaneously transmitted data streams, as well as the beam pattern for each transmitted data stream, can be managed and controlled by the corresponding protocol to optimize the 4th and 5th networks' capacity.

Therefore, such integration of a MIMO system with LTE-A technology allows us to avoid, in practice, all the drawbacks related to the previous generations described above. It also allows designers of modern 4th generation of wireless networks improve their GoS and QoS, protecting against ISI and ICI caused by multipath fading phenomena, mentioned in Section 1, increase their frequency spectral allocation, and finally, minimize bit error rate and packet error rate. All these aspects fully correspond to the main aim of the authors of this book, that is, show the reader on how should be completely integrated all basic components of the wireless network:

— the physical layer, based on multipath fading phenomena;

— signal processing, based on modulation techniques;

— protocols and accesses of multiuser servicing;

— antenna design layer, based on performance of multi-beam and phased-array antennas, and so on.

Of course, there are other components of each wireless network — the architecture and electronic circuits, based on different elements of the system hardware, such as RAKE detector, correlators, filters, and so on. These aspects are out of scope of this special issue, and we refer the reader to the excellent books and articles presented below in bibliography [4–9, 11–20].

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Эволюция многопроцессорных систем связи — сотовых и несотовых — в исторической перспективе. Часть 4

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Постановка проблемы: целью данного обзора является анализ эволюции систем беспроводной связи от второй генерации (2G) до пятой генерации (5G), а также изменения технологий и их существующих теоретических основ и протоколов — от Bluetooth, WLAN, WiFi и WiMAX до LTE, OFDM/OFDMA, MIMO и LTE/MIMO — продвинутых технологий с новой иерархической структурой дизайна сотовых карт фемто/пико/микро/макро. **Методы:** использованы новые теоретические подходы для описания продвинутых технологий, таких как многопользовательская техника разделения пользователей, OFDM и OFDM новейший подход, новые аспекты описания MIMO-систем на базе использования многолучевых антенн, дизайн различных сотовых карт на основе новых алгоритмов построения фемто/пико/микро/макро сот, а также новой методологии интегрирования новой MIMO/LTE-системы с помощью многолучевых антенн. **Результаты:** создана новая методология описания многопользовательского разделения, использования комбинированной OFDM/OFDMA-модуляции для обхождения интерференции между пользователями и между символами в новых многопроцессорных системах, мультипликативных шумов, имеющих место в беспроводных многопроцессорных системах связи, вызванных явлениями многолучевости. В итоге предложено, как обойти эффекты распространения, имеющие место в наземных каналах связи, используя комбинацию MIMO- и LTE-технологий, основанных на применении многолучевых антенн. Для этих целей разработан новый стохастический подход к проблеме, учитывающий особенности застройки земной поверхности, такие как профиль застройки домов, плотность застройки домов вокруг антенн базовой станции и пользователей и т. д. Эти характеристики позволяют в итоге оценить эффекты фединга как источника мультипликативного шума. **Практическая значимость:** новая методология оценки эффектов, созданных мультипликативным шумом, интерференцией между пользователями и между символами, имеющими место в наземных системах беспроводной связи, позволяет прогнозировать практические аспекты существующих и новых многопроцессорных беспроводных систем связи, такие как емкость (количество) пользователей и спектральная эффективность каналов пользователей для различных конфигураций построения сот — фемто/пико/микро/макро, а также новейших конфигураций систем MIMO/LTE для построения будущих систем 4-го и 5-го поколений.

Ключевые слова — емкость сети, релизы сети LTE, множественный вход-множественный выход (MIMO), многопользовательский (MU), одиночный вход-одиночный выход (SISO), одиночный вход-множественный выход (SIMO), единственная несущая частота (SC), единственный пользователь (SU), пользовательское оборудование (UE), беспроводная сеть WiFi, городская беспроводная сеть WiMAX.

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