Quasi-Quadrature Modulation Method for Power-Efficient Video Transmission Over LTE Networks

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***Abstract*—New emerging services, such as real-time video streaming or video on demand, are causing rapid growth in packet transmission over wireless networks. Unlike voice calls, for which the duration is usually not very long, video streaming applications require continuous transmission for a long time. Therefore, video streaming applications in mobile networks consume more energy compared with voice calls. Thus, the task of optimizing data transmission algorithms has become more important during the last few years. Apparently, the majority of multimedia traffic is video transmission. These applications consume much more power, compared with audio or general data transmission, because of higher throughput requirements. This paper addresses the problem of decreasing power consumption due to video transmission applications in Long-Term Evolution (LTE) networks. There are existing solutions for managing power consumption during video transmission. In particular, Third-Generation Partnership Project LTE Advanced (LTE-A) has defined the discontinuous reception/transmission (DRX/DRT) mechanism to allow devices to turn off their radio interfaces and go to sleep in various patterns. Some other similar solutions suggest DRX/DRT optimization to maximize the sleep periods of devices while guaranteeing quality of service in multimedia applications. However, existing solutions for packet transmission optimization are not very effective without physical-layer optimization. However, existing solutions for packet transmission optimization are not very effective without physical-layer optimization. We suggest a new method of modulation for improving energy efficiency of wireless video transmission. Four different schemes of quasi-quadrature modulation using multiple-input–multiple-output (MIMO) techniques with different quality of service performances are proposed in this paper. We simulate H.264/AVC video transmission. Results confirm the theoretical analysis. The proposed approach is able to improve energy efficiency while providing the same packet loss probability.**

***Index Terms*—Long-Term Evolution (LTE), power efficiency, quasi-quadrature modulation method, video transmission.**

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I. Introduction

Wireless telecommunications networks and broadband access consume a huge amount of energy for data transmission. Telecommunications accounts for at least 4% of global electricity consumption [1]. According to an International Telecommunications Union report, energy efficiency is the key issue in the telecommunications industry [2]. The goal is to design telecommunications networks with greater energy efficiency. Green trends are already supported by different operators.

Recently, the problem of energy consumption has become more important because of the rapid growth in packet traffic. Green techniques in cellular networks mainly depend on radio access network infrastructure design and the efficiency of the electronic components, effective network planning, efficient transmission techniques, and physical-layer characteristics (modulation, coding, etc.) [3]–[5].

To manage power consumption, Third-Generation Partnership Project Long Term Evolution Advanced has defined the discontinuous reception/transmission (DRX/DTX) mechanism, which allows devices to turn off their radio interfaces and go to sleep in various patterns. One paper addresses DRX/DTX optimization by asking how to maximize the sleep periods of devices while guaranteeing quality of service, particularly when it comes to traffic bit rate, packet delay, and packet loss rate in multimedia applications [6].

Evaluation of the potential of such traffic shaping mechanisms to save energy of smartphones to which audio and video are streamed over third-generation (high-speed packet access) and Long-Term Evolution (LTE) networks was provided by Liang *et al.* [7].

Apparently, the majority of multimedia traffic is video transmission. These applications consume much more power, compared with audio or general data transmission, because of higher throughput requirements. Therefore, existing solutions for packet transmission optimization are not very effective without physical-layer optimization. The communication between eNodeB and the mobile customer requires much power to provide the necessary SNR. The impact of the physical layer on energy consumption of wireless networks was analyzed by Stryhalyuk *et al.* [8]. Similar studies [9]–[11] suggest cognitive radio access techniques for increasing the energy and spectral efficiency of cognitive radio networks. The cognitive radio approach for increasing energy efficiency of GSM/LTE converged network was proposed by Maksymyuk *et al.* [12], [13]. The impact of multiuser transmission on power efficiency was analyzed by Yaremko *et al.* [14], and a power control method was suggested in [15]. Both papers show that the characteristics of the physical layer are important factors for cell and network energy consumption and depend on the traffic intensity and the environment of each scenario that needs to be considered when deploying the system.

The relationship between the energy efficiency and spectrum efficiency in a two-cell cellular network was obtained by Ge *et al.* [16], [17], and the impact of multiantenna on the energy efficiency of the cellular network was analyzed and modeled based on two-state Markovian wireless channels. A significant role in energy-efficient wireless transmission is played by modulation techniques. The main goal of each modulation technique is to provide high throughput with proper quality in the presence of noise, with only a small amount of energy and minimum bandwidth. The most useful method in state-of-the-art wireless networks is quadrature modulation, which is used in LTE, Worldwide Interoperability for Microwave Access, Digital Video Broadcasting–Terrestrial (T2), Wi-Fi, and other standards of radio access networks.

Quadrature modulation schemes are well known and have been used for a long time in wireless communications. The most popular digital modulation scheme is quadrature amplitude modulation (QAM), where both in-phase and quadrature components are modulated by independent sequences of rectangular pulses. The idea of adapting modulation to minimize energy consumption is one of the new techniques and should be considered. One of the first steps in this area [18] provides balance between modulation scaling and voltage scaling.

Kader *et al.* considered the unequal error protection (UEP) and median filtering for transmission of images over poor wireless channels usually encountered over cellular mobile networks [19]. For this reason, they proposed the hierarchical QAM (HQAM) method that provides UEP for the image data transmission. In HQAM, nonuniform signal constellation is used to provide different degrees of protection to the significant and nonsignificant bits within the image data at lower SNR in a wireless channel.

In [20], Fu *et al.* developed an energy-efficient transmission scheme for Reed–Solomon-coded QAM systems. This scheme is capable of adjusting the modulation level and code rate of Reed–Solomon codes based on the proposed scheme and thus efficiently reduce the energy consumption.

In [21], Miao *et al.* developed energy-efficient schemes with significantly lower complexity when compared with iterative approaches, by considering time-averaged bits-per-Joule metrics. They considered an uplink OFDMA system where multiple users communicate to a central scheduler over frequency-selective channels with high energy efficiency. The scheduler allocates the system bandwidth among all users to optimize energy efficiency across the whole network. Using time-averaged metrics, they derived energy optimal techniques in "closed form" for per-user link adaptation and resource scheduling across users.

Another approach minimizes communication energy by optimizing transmission time [22]. Prabhu *et al.* [23] were interested in finding optimal constellation size and transmit power for minimizing energy per successfully received bit in a point-to-point wireless link with a simple automatic repeat request (ARQ) protocol.

In this paper, we propose another approach to minimizing energy per transmitted symbol by developing the quasi-quadrature modulation technique. This technique is the same as pulse amplitude modulation on the transmission side, but the receiver-demodulated signal considers it a proper QAM signal. This technique transmits only half a QAM symbol; thus, power consumed by packet transmission is cut in half.

The major contributions of this paper are the following.

1) We suggest a state-of-the-art method for signal modulation, which decreases power consumption of video data transmission while providing the same packet loss probability.
2) We make recommendations for proper use of proposed modulation schemes for LTE physical channels according to the channel quality identifier (CQI) supported in LTE-A networks.
3) We simulate video data transmission over an LTE network and evaluate the impact of packet size on packet loss probability for different modulation schemes.

This paper is organized as follows. Section II covers the principles of signal modulation and allocation in the LTE downlink channel. Section III covers the theoretical description and mathematical proof of the proposed quasi-quadrature modulation method. Section IV presents a numerical example with results and analysis. Section V concludes this paper.

II. Principles of Signal Modulation and Allocation in Long-Term Evolution Downlink Channel

In LTE, a radio interface orthogonal frequency-division multiple access (OFDMA) scheme is used for user allocation [24], [25]. Transmissions are organized into 10-ms frames, each of which is comprised of ten 1-ms subframes. Each subframe is divided into two slots. The smallest modulation structure in LTE is the resource element (RE). A RE is one 15-kHz subcarrier by one symbol with duration of 66.7 μs. REs aggregate into a resource block, which contains 12 consecutive subcarriers in the frequency domain and six or seven symbols in the time domain. Each RE carries one symbol modulated by quadrature phase-shift keying (QPSK) (4-QAM), 16-QAM, or 64-QAM.

Considering the classic QAM, the input bit stream is divided into two parallel streams. Both streams are modulated by two carrier waves, usually sinusoids, which are out of phase with each other by 90°. Thus, the two obtained components form a 2-D constellation diagram. Each point in the constellation presents a symbol of the $I-Q$ grid, i.e.,

$$A = [I, Q] = \{a_0, \ldots, a_{M-1}\} \quad (1)$$

where I and Q are in-phase and quadrature components of the signal, respectively, and a denotes a digital bit (0 either 1). The number of bits per symbol for multilevel QAM (M-QAM) modulation is calculated as

$$N = \log_2 M. \tag{2}$$

Thus, the mathematical representation of the QAM signal is defined as follows:

$$s_{\mathrm{QAM}}(t) = g(t)A_I \cos(\omega t) - g(t)A_Q \sin(\omega t) \tag{3}$$

where $g(t)$ is a pulse shape in time domain, A_I and A_Q are in-phase and quadrature symbol amplitudes respectively, and $\omega = 2\pi f$, with f being the frequency of the signal. To further simplify calculation, we assume that $g(t)$ is rectangular pulse shape, and its value is constant during 66.7 μs of modulated symbol transmission time.

Since the downlink channel of LTE uses orthogonal frequency-division multiplexing (OFDM), the transmitted signal is defined as follows:

$$s_{\mathrm{OFDM/QAM}}(t) = \sum_{k=1}^{N} g_k(t)\left[A_{kI}\cos(\omega kt) - A_{kQ}\sin(\omega kt)\right] \tag{4}$$

where k is the subcarrier index, and N is the number of OFDM subcarriers.

The instantaneous power of the signal is defined as

$$P(t) = g_k^2(t)\left[A_{kI}\cos(\omega kt) - A_{kQ}\sin(\omega kt)\right]^2. \tag{5}$$

Suppose that each symbol is modulated with the same pulse shape. Then, the signal energy for a QAM signal is calculated as

$$E_{\mathrm{QAM}} = g^2(t)\int_0^{66.7}\left[A_I\cos(\omega kt) - A_Q\sin(\omega kt)\right]^2 dt. \tag{6}$$

Equation (6) denotes the energy of a QAM symbol of one RE. However, (6) cannot be computed by simple integration. Therefore, we use partial integration to calculate the total signal energy. Equation (6) can be expanded as follows:

$$E_{\mathrm{QAM}} = g^2(t)\int_0^{66.7}\left(A_I^2\cos^2(\omega t) - 2A_IA_Q\cos(\omega t)\right.$$
$$\left.\times\sin(\omega t) + A_Q^2\sin^2(\omega t)\right)dt. \tag{7}$$

By representing the integral of the sum as a sum of integrals and factoring out constants, we obtain

$$E_{\mathrm{QAM}} = g^2(t)\cdot\left[A_I^2\int_0^{66.7\,\mu s}\cos^2(\omega t)\,dt - 2A_IA_Q\right.$$
$$\left.\times\int_0^{66.7\,\mu s}\cos(\omega t)\sin(\omega t)\,dt + A_Q^2\int_0^{66.7\,\mu s}\sin^2(\omega t)\,dt\right]. \tag{8}$$

For substitution, we denote

$$\begin{aligned} &u = \cos(\omega t) \quad du = -\sin(\omega t)\,dt \\ &\cos^2(\omega t) = \left(\frac{1}{2} + \frac{\cos(2\omega t)}{2}\right) \\ &\sin^2(\omega t) = \left(\frac{1}{2} - \frac{\cos(2\omega t)}{2}\right) \\ &x = 2\omega t \quad dx = \omega 2\,dt. \end{aligned} \tag{9}$$

After that, (8) is changed as follows:

$$\begin{aligned} E_{\mathrm{QAM}} = g^2(t)\cdot\Bigg[&A_I^2\int_0^{66.7\,\mu\mathrm{S}}\left(\frac{1}{2} + \frac{\cos(x)}{2}\right)dx \\ &- 2A_IA_Q\int_0^{66.7\,\mu\mathrm{S}} u\,du \\ &+ A_Q^2\int_0^{66.7\,\mu\mathrm{S}}\left(\frac{1}{2} - \frac{\cos(x)}{2}\right)dx\Bigg] \\ = -g^2(t)\cdot\Bigg[&\frac{A_I^2}{2}\int_0^{66.7\,\mu\mathrm{S}} 1\,dt + \frac{A_I^2}{2}\int_0^{66.7\,\mu\mathrm{S}}\cos(x)dx \\ &- 2A_IA_Q\int_0^{66.7\,\mu\mathrm{S}} u\,du + \frac{A_Q^2}{2}\int_0^{66.7\,\mu\mathrm{S}} 1\,dt \\ &- \frac{A_Q^2}{2}\int_0^{66.7\,\mu\mathrm{S}}\sin(x)dx\Bigg]. \end{aligned} \tag{10}$$

By computing each integral in (10) independently, we obtain

$$\begin{aligned} E_{\mathrm{QAM}} = g^2(t)\cdot\Bigg[&\frac{A_I^2\omega t}{2} + \frac{A_I^2\sin(x)}{4} + u^2A_IA_Q \\ &+ \frac{A_Q^2\omega t}{2} - \frac{A_Q^2\sin(x)}{4}\Bigg]\Bigg|_0^{66.7\,\mu\mathrm{S}}. \end{aligned} \tag{11}$$

With back substitution of (9), the energy of QAM is calculated as follows:

$$\begin{aligned} E_{\mathrm{QAM}} = \frac{g^2(t)}{4}\cdot\big[&2\left(A_I^2 + A_Q^2\right)\omega t + 4A_IA_Q\cos^2(\omega t) \\ &+ \left(A_I^2 - A_Q^2\right)\sin(2\omega t)\big]\big|_0^{66.7\mu\mathrm{S}}. \end{aligned} \tag{12}$$

III. Quasi-Quadrature Modulation Scheme for Energy-Saving Downlink Transmission

We propose a new method of quasi-QAM (QQAM) to improve energy efficiency. As mentioned in Section II, ordinary QAM suggests two (in-phase and quadrature) signal components. We modulate signal only by in-phase component of the QAM signal. However, the receiver is able to represent the input signal as a two-component signal, providing special mapping associations.

For mathematical representation of a QQAM signal, we transform (3) without the quadrature component as follows:

$$s_{\mathrm{QQAM}}(t) = g(t)A\cos(\omega t). \tag{13}$$

Thus, the mathematical representation of the OFDM/QQAM signal becomes

$$s_{\mathrm{OFDM/QQAM}}(t) = \sum_{k=1}^{N} g_k(t) A_k \cos(\omega k t). \tag{14}$$

The instantaneous power of the OFDM/QQAM signal is calculated as

$$P(t) = g^2(t) A_I^2 \cos(\omega t). \tag{15}$$

Then, the total energy of the OFDM/QQAM signal is

$$E_{\mathrm{QQAM}} = g^2(t) A_I^2 \int_0^{66.7\mu\mathrm{S}} \cos^2(\omega t)\, dt. \tag{16}$$

By modifying (16) according to (9), we have

$$\begin{aligned} E_{\mathrm{QQAM}} &= g^2(t) A_I^2 \int_0^{66.7\mu\mathrm{S}} \left(\frac{1}{2} + \frac{\cos(x)}{2}\right) dx \\ &= g^2(t) \left[\frac{A_I^2}{4} \int_0^{66.7\mu\mathrm{S}} \cos(x)\, dx + \frac{A_I^2}{2} \int_0^{66.7\mu\mathrm{S}} 1\, dx\right]. \end{aligned} \tag{17}$$

Then, we integrate the sum and factor out the constants to obtain

$$\begin{aligned} E_{\mathrm{QQAM}} &= g^2(t) \cdot \left(\frac{A_I^2 \omega t}{2} + \frac{A_I^2 \sin(2\omega t)}{4}\right) \\ &= \frac{g^2(t)}{2} A_I^2 \left(\omega t + \cos(\omega t) \sin(\omega t)\right). \end{aligned} \tag{18}$$

The energy gain is calculated by comparing (12) and (18) as follows:

$$\begin{aligned} G_E = \frac{2}{A_I^2 \left(\cos(\omega t)\sin(\omega t) + \omega t\right)} \cdot \Big[A_I A_Q \cos^2(\omega t) \\ + \frac{\sin(2\omega t)\left(A_I^2 - A_Q^2\right)}{4} + \frac{\left(A_I^2 + A_Q^2\right)\omega t}{4}. \end{aligned} \tag{19}$$

As shown in (19), only half of the energy is needed for transmitting in-phase components with the proposed QQAM. The transmitter sends only the in-phase component, consuming half the energy. However, the receiver uses the association table for reconstructing the quadrature component of the signal. Thus, we provide both in-phase and quadrature components of the QAM symbol at the receiver side by ordinary quadrature modulation.

Moreover, this approach also allows for the increase of the SNR for input at the receiver by transmitting the in-phase component with the same energy as both in-phase and quadrature components in QAM. In this case, the quality of packet data transmission doubles. We suggest using the 4 × 4 multiple-input–multiple-output (MIMO) transmission scheme with spatial multiplexing. In this case, four antennas transmit different signals simultaneously in one spectrum by polarization division [26]. Each antenna is associated with a unique modulation mapping.

To achieve better scalability of resource allocation, we suggest alternate MIMO transmission schemes for QPSK modulation and concerted MIMO transmission for 64-ary QAM. For 16 QAM, both cases are allowed.

TABLE I
MODULATION MAPPING ASSOCIATIONS FOR 16-QQAM

Index of antenna	In-phase amplitude	Quadrature amplitude
Antenna 1	-3/√10	-3/√10
	-1/√10	-1/√10
	1/√10	1/√10
	3/√10	3/√10
Antenna 2	-3/√10	3/√10
	-1/√10	1/√10
	1/√10	-1/√10
	3/√10	-3/√10
Antenna 3	-3/√10	1/√10
	-1/√10	3/√10
	1/√10	3/√10
	3/√10	1/√10
Antenna 4	-3/√10	-1/√10
	-1/√10	-3/√10
	1/√10	-3/√10
	3/√10	-1/√10

A. *Alternate MIMO Quasi-QPSK Mapping*

In this scheme, the base station transmitter sends only one symbol with amplitude equal to $1/\sqrt{2}$, by one of four antennas. The selection of the antenna depends on the $I-Q$ combination of the given symbol. Each point of the QPSK constellation is presented by one antenna as follows.

- First antenna: $A_I = 1/\sqrt{2}$, and $A_Q = 1/\sqrt{2}$;
- Second antenna: $A_I = 1/\sqrt{2}$, and $A_Q = -1/\sqrt{2}$;
- Third antenna: $A_I = -1/\sqrt{2}$, and $A_Q = 1/\sqrt{2}$;
- Fourth antenna: $A_I = -1/\sqrt{2}$, and $A_Q = -1/\sqrt{2}$.

Each receiver's antenna is able to represent the obtained symbol as an $I-Q$ symbol of QPSK modulation. Thus, the bit rate of the proposed scheme is the same as QPSK, but the power consumption for symbol transmission is half that of QPSK.

B. *Alternate MIMO 16-Quasi-QAM Mapping*

Consider a similar scheme for 16-ary modulation. The base-station transmitter sends in-phase symbols with amplitudes from the set $\{-3/\sqrt{10}, -1/\sqrt{10}, 1/\sqrt{10}, 3/\sqrt{10}\}$.

However, at the receiver, each of the receiver antennas associate the quadrature amplitude with the obtained in-phase amplitude as presented in Table I.

Similar to quasi-QPSK (QQPSK), the receiver represents the obtained symbol as an $I-Q$ symbol of the 16-QAM constellation. Each antenna associates it with only four symbols instead of 16 (i.e., the bit rate of the proposed scheme is the same as 16-QAM but needs only half the power).

C. *Concerted MIMO 16-Quasi-QAM Mapping*

This modulation scheme is similar to alternate-MIMO 16-QQAM presented earlier (i.e., $I-Q$ corresponds in the same way as in Table I). However, there are two differences: 1) new mapping in which one symbol presents only two bits instead of four; and 2) four antennas transmit simultaneously in one subcarrier (i.e., in this case, MIMO 4 × 4 is used properly as a spatial multiplexing scheme).

TABLE II
MODULATION MAPPING ASSOCIATIONS FOR 64-QQAM

Index of antenna	In-phase amplitude	Quadrature amplitude	Index of antenna	In-phase amplitude	Quadrature amplitude
Antenna 1	-7/√42	-7/√42	Antenna 3	-7/√42	1/√42
	-5/√42	-5/√42		-5/√42	3/√42
	-3/√42	-3/√42		-3/√42	5/√42
	-1/√42	-1/√42		-1/√42	7/√42
	1/√42	1/√42		1/√42	7/√42
	3/√42	3/√42		3/√42	5/√42
	5/√42	5/√42		5/√42	3/√42
	7/√42	7/√42		7/√42	1/√42
Antenna 2	-7/√42	7/√42	Antenna 4	-7/√42	-1/√42
	-5/√42	5/√42		-5/√42	-3/√42
	-3/√42	3/√42		-3/√42	-5/√42
	-1/√42	1/√42		-1/√42	-7/√42
	1/√42	-1/√42		1/√42	-7/√42
	3/√42	-3/√42		3/√42	-5/√42
	5/√42	-5/√42		5/√42	-3/√42
	7/√42	-7/√42		7/√42	-1/√42

D. Concerted MIMO 64-Quasi-QAM Mapping

This scenario is very similar but represents symbols of a 64-QAM constellation. $I-Q$ associations at the receiver are presented in Table II.

As shown in Table II, each receiver antenna is able to represent eight symbols of the 64-QAM constellation. Each symbol in this case represents three bits and the total number of transmitted bits per 15 kHz $\times$ 66.7 μs RE increases to 12. Fig. 1 shows the associated constellation for suggested modulations in the $I-Q$ plane.

The circular areas in Fig. 1 show the corresponding points of each antenna. The solid circle represents the first antenna, the dashed circle is the second antenna, the dotted circle is the third antenna, and the dash-dotted line is the fourth antenna, respectively. This technique uses MIMO 4 $\times$ 4 transmission, but during the symbol interval (66.7 μs), the transmission scheme is equal to single-input–single-output (SISO) 1 $\times$ 1. In the case of QQPSK modulation [see Fig. 1(a)], there are four alternative antenna-to-antenna schemes. The four schemes depend for users on the necessary combination of bits from the set {00, 01, 10, 11}. Therefore, knowing the number of antennas that received the signal, user equipment (UE) corresponds to I and Q amplitudes to determine the input symbol. This scheme is less complex and more power efficient than ordinary QPSK modulation.

In Fig. 1(b), each symbol of the alternate-MIMO 16-QQAM constellation represents four bits as ordinary 16-QAM. However, four nonoverlapped subconstellations are assigned to four separate antennas. This approach is less complex and doubles the energy efficiency compared with ordinary 16-QAM. We assume that 16-QQAM with alternate MIMO is an alternative scheme to 16-QAM.

In Fig. 1(c), each symbol of the 16-QQAM constellation represents two bits instead of four bits. However, four nonoverlapped symbols are transmitted simultaneously by four antennas, and the total number of transmitted bits increases to eight bits per 15 kHz $\times$ 66.7 μs RE. The antennas' assignments are exactly the same as in the previous cases. We position this scheme between SISO 64-QAM, which transmits six bits per RE, and MIMO 2 $\times$ 2 64-QAM, which transmits 12 bits per RE, as an alternative to MIMO 2 $\times$ 2 16-QAM.

As shown in Fig. 1(d), in the case of 64-QQAM, only 32 symbols of the 64-QAM constellation can be represented by associating quadrature amplitude with in-phase amplitude in the MIMO 4 $\times$ 4 scheme. The other 32 symbols cannot be used without increasing the number of antennas. Thus, we position this scheme between MIMO 2 $\times$ 2 16-QAM, which transmits eight bits per RE, and the MIMO 4 $\times$ 4 16-QAM scheme, which transmits 16 bits per RE.

IV. SIMULATION AND RESULTS

A. Achievable Video Transmission Rates and Radio Resource Allocation in LTE Downlink Channel

Consider the LTE downlink frame in which the frame duration is 10 ms. N subcarriers transmit REs during 140 time intervals of the frame. Thus, the total number of REs in the frame is

$$N_{\mathrm{RE}} = 140 \cdot N_{\mathrm{sub}}. \tag{20}$$

However, not all elements are used for users' data transmission because part of the elements are used for signaling data information in LTE. The LTE frame carries physical channels and physical signals. Channels carry information received from high layers. The 10-ms downlink frame contains the following channels.

Physical Downlink Shared Channel: The physical downlink shared channel (PDSCH) is used to transport user data and is designed for high data rates. In general, modulation options include QPSK, 16-QAM, and 64-QAM. In addition to the standard set of modulation, our approach allows QQPSK, SISO 16-QQAM, MIMO 16-QQAM, and MIMO 64-QQAM and thus improves scalability of CQI. The REs associated with this channel are shared among users via OFDMA.

Physical Broadcast Channel: Every 40 ms, the physical broadcast channel sends cell-specific system identification and access control parameters using QPSK modulation for our suggested QQAM.

Physical Control Format Indicator Channel: The physical control format indicator channel (PCFICH) is a value that ranges between 1 and 3. The value of the PCFICH indicates the number of OFDM symbols used for the transmission of physical downlink control channel (PDCCH) information in a subframe. The PCFICH also uses QPSK or QQPSK modulation.

Physical Hybrid ARQ Indicator Channel: The physical hybrid ARQ indicator channel carries acknowledged/nonacknowledged (ACK/NACK) messages, which confirm the delivery or request the retransmission of data blocks. The ACKs and NACKs are part of the HARQ mechanism.

Physical Downlink Control Channel: This channel provides information about uplink and downlink resource allocations. The PDCCH allocates up to the first three OFDM symbols

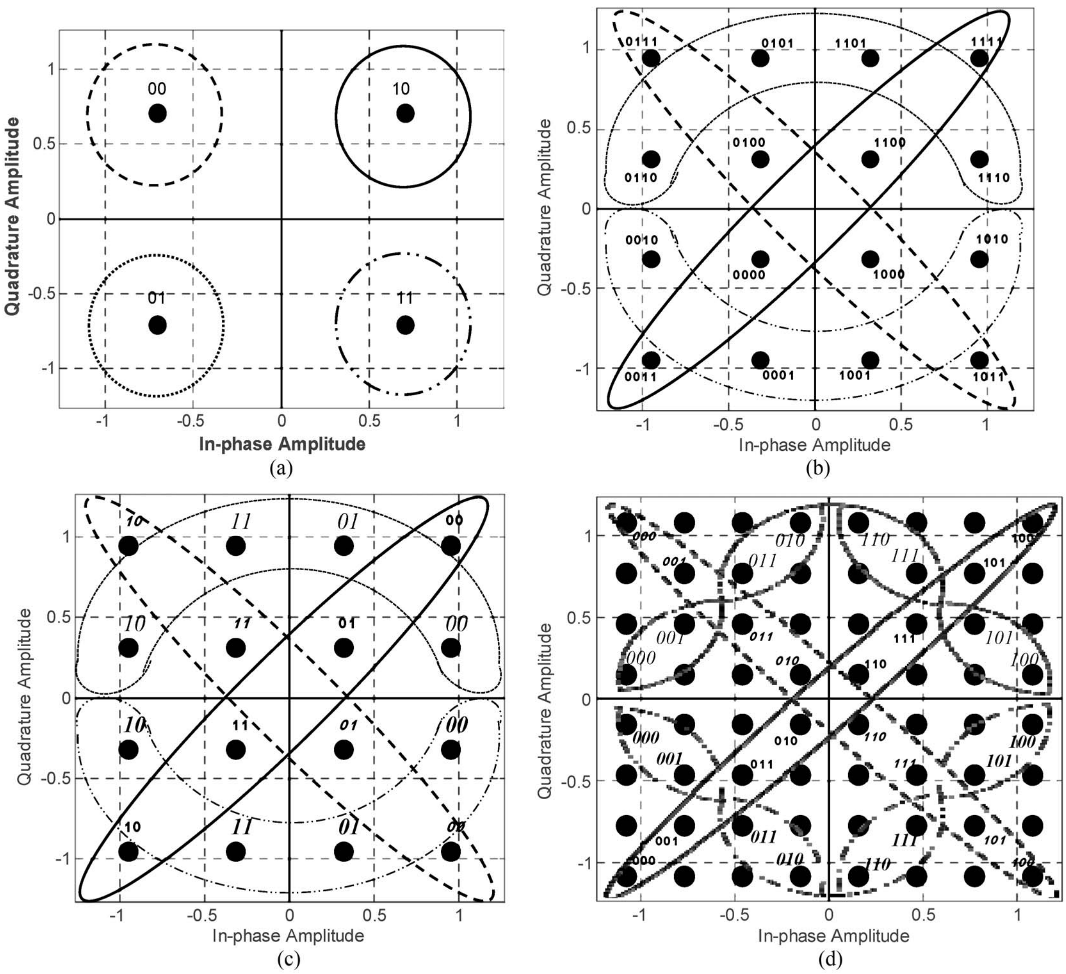

Fig. 1. Mutual constellation of four receiver antennas for (a) QQPSK modulation, (b) 16-QQAM with alternate-MIMO scheme, (c) 16-QQAM with concerted-MIMO scheme, and (d) 64-QQAM with concerted-MIMO scheme.

in the first slot of a subframe. QPSK or QQPSK modulation is used for this channel. The number of symbols used for the PDCCH depends on value of the PCFICH. The PDCCH is padded with dummy signals to ensure that the combined PDCCH with dummies occupies an integer number of symbols.

Reference Signal: UEs use a reference signal (RS) for evaluation of downlink channel conditions and to determine the channel impulse response. The RS is the product of a 2-D orthogonal sequence and a 2-D pseudorandom sequence. There are three different sequences available for the orthogonal sequence, and 170 possible sequences for the pseudorandom numerical, the specification identifies 504 RS sequences. REs allocated to RSs on one antenna are DTX on the other antennas.

Synchronization Signal (P-SS and S-SS): UEs use the primary synchronization signal (P-SS) for timing and frequency acquisition during cell search. The P-SS carries part of the cell ID and provides slot timing (0.5 ms) synchronization. P-SS is transmitted on 62 of the reserved 72 subcarriers (six resource blocks) around dc on symbol 6 in slots 0 and 10. UEs use the secondary synchronization signal (S-SS) in cell search. It provides frame timing (10 ms) synchronization and the remainder of the cell ID. S-SS is transmitted on 62 of the reserved 72 subcarriers (6 resource blocks) around dc on symbol 5 in slots 0 and 10. Synchronization signals use binary phase-shift keying modulation. The five subcarriers above the synchronization signals and the five subcarriers below the synchronization signals are reserved and transmitted as DTX.

As previously mentioned, for user data transmission, LTE uses PDSCH channels. Each PDSCH channel sends a modulation symbol. The smallest resource, which is occupied by one user, is two consecutive resource blocks: 12 subcarriers and 14 time intervals. Two resource blocks transmit during a 1-ms subframe. Thus, the period of subframe transmission is 10 ms.

Note that the number of PDSCH channels per resource block may be different for each block and depend on service channel configuration. However, for simplicity of calculation, we assume that the number of PDSCH channels is the same for each resource block.

Thus, the achievable rate of video transmission per user of M-QAM or M-QQAM is calculated as follows [27]:

$$R_{\mathrm{PDSCH}} = N_{\mathrm{PDSCH}} \cdot 10 \cdot \log_2 M. \tag{21}$$

Calculated achievable transmission rates are presented in Table III.

Results presented in Table III show that proposed quasi-quadrature modulation schemes are able to achieve transmission rates comparable to ordinary quadrature modulations.

TABLE III
ACHIEVABLE RATES (MB/S) AND NORMALIZED ENERGY OF DIFFERENT MODULATION SCHEMES

Modulation type	Antenna scheme	Bits per RE	Normalized transmitted energy per symbol	Equal Received Energy per symbol	Bandwidth, MHz					
					1.4	3	5	10	15	20
QPSK	SISO	2	Full	Full	0.169	0.439	0.739	1.489	2.239	2.989
QQPSK	Alternate-MIMO	2	Half(Full)	Full(Double)						
QPSK	MIMO 2x2	4	Full	Full	0.324	0.842	1.418	2.858	4.298	5.738
16 QAM	SISO	4	Full	Full	0.337	0.877	1.477	2.977	4.477	5.977
16 QQAM	Alternate-MIMO	4	Half(Full)	Full(Double)						
64 QAM	SISO	6	Full	Full	0.506	1.316	2.216	4.466	6.716	8.966
QPSK	MIMO 4x4	8	Full	Full	0.611	1.590	2.678	5.398	8.118	10.08
16 QAM	MIMO 2x2	8	Full	Full	0.647	1.684	2.836	5.716	8.596	11.48
16 QQAM	Concerted-MIMO	8	Half(Full)	Full(Double)	0.675	1.755	2.955	5.995	8.955	11.96
64 QAM	MIMO 2x2	12	Full	Full	0.970	2.526	4.254	8.574	12.89	17.21
64 QQAM	Concerted-MIMO	12	Half(Full)	Full(Double)	1.012	2.632	4.432	8.932	13.43	17.93
16 QAM	MIMO 4x4	16	Full	Full	1.221	3.180	5.356	10.08	16.24	20.60
64 QAM	MIMO 4x4	24	Full	Full	1.832	4.769	8.033	16.19	24.35	32.51

However, as mentioned earlier, quasi-quadrature modulation reduces power consumption per symbol transmission. We suggest various scenarios for quasi-quadrature modulation for balancing between transmitted power and energy per transmitted bit. The lowest transmission power is half the transmission power of QPSK and QAM. Maximum power transmission is equal to full power of ordinary quadrature modulation and thus provides signal equal to double the energy at the receiver.

B. Evaluation of Packet Loss Probability

Note that, regardless of the differences between ordinary quadrature modulation and quasi-quadrature modulation, the BER of these schemes is the same and depends only on modulation order. Thus, packet loss probability directly depends on modulation order and SNR as follows:

$$P_{\text{loss}} = 1 - \left[1 - \frac{2(1-M^{-1})}{\log_2 M} \cdot Q\left(\sqrt{\frac{3\log_2 M}{(M^2-1)}\frac{2E_b}{N_0}}\right)\right]^b \quad (22)$$

where E_b is energy per bit, N_0 is noise power spectral density, b is packet size (in bits), and $Q(f)$ is error function. Note that E_b equals energy per bit at the UE antenna. Therefore, with quasi-quadrature modulation, actual transmitted energy per bit is half that of ordinary QAM or QPSK. Note that energy per successful transmitted packet is equal to packet length.

Since user data are transmitted over the PDSCH channel, the average number of occupied REs per subframe is 140. Thus, one subframe transmits from 280 to 3360 bits, depending on the modulation scheme.

We assume that QQPSK modulation is useful only for signaling data because of the low rate. For video and other data transmissions, we use one of the modulation schemes presented in Table III, depending on the necessary throughput and available free bandwidth. We assume that the proposed approach could be combined with existing methods of adaptive transmission and spectrum sensing. The primary scheme is QQAM because of better energy efficiency. QQAM is used, whereas cells are not overloaded and enough spectrum is available to achieve the necessary throughput. When cells are overloaded, the modulation scheme switches to QAM with a proper order.

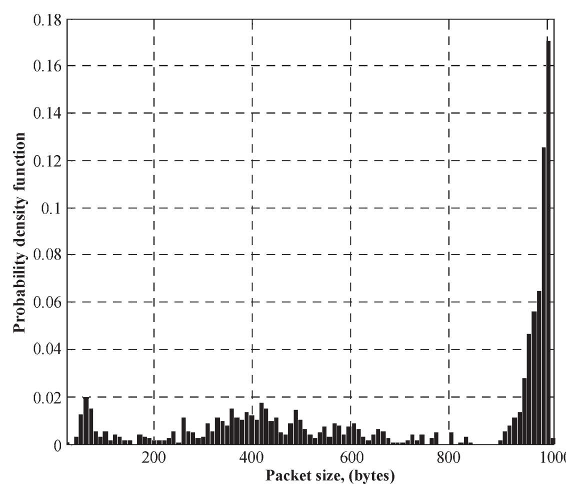

Fig. 2. Probability density function of packet size.

C. Simulation and Results

We developed the video transmission scheme in the NS-2 simulator. Video was encoded using the H.264/AVC standard [28]. There are 1000 transmitted packets, and the total transmitted data are 1 Mb approximately, which is equivalent to ∼20 s of video stream with the following encoding parameters: frame rate of 30 frames/s, bit rate of 400 Kb/s, and average peak SNR of 38.68 dB. To compare packet loss for three modulation schemes, we set up constant bit rate (CBR) packet size at 1000 B and CBR interval at 0.008. Packet size is a random variable with a probability density function as shown in Fig. 2.

TABLE IV
RESULTS OF COMPARATIVE SIMULATION OF QUASI-QUADRATURE AND ORDINARY QUADRATURE MODULATIONS SCHEMES

BER	Required energy to noise ratio, dB				BER	Required energy to noise ratio, dB			
	Symbol energy to noise ratio		Bit energy to noise ratio			Symbol energy to noise ratio		Bit energy to noise ratio	
	16 QAM	*16 QQAM*	*16 QAM*	*16 QQAM*		*64 QAM*	*64 QQAM*	*64 QAM*	*64 QQAM*
1,41E-01	2	-1	-4		2,00E-01	3	0	-5	
1,19E-01	4	1	-2		1,78E-01	6	3	-2	
9,77E-02	6	3	0		1,57E-01	9	6	1	
7,75E-02	8	5	2		1,37E-01	12	9	4	
5,86E-02	10	7	4		1,19E-01	15	12	7	
4,19E-02	12	9	6		1,01E-01	18	15	10	
2,79E-02	14	11	8		8,38E-02	21	18	13	
1,70E-02	16	13	10		6,76E-02	24	21	16	
9,25E-03	18	15	12		5,23E-02	27	24	19	
4,39E-03	20	17	14		3,85E-02	30	27	22	
1,75E-03	22	19	16		2,65E-02	33	30	25	
5,65E-04	24	21	18		1,69E-02	36	33	28	
1,39E-04	26	23	20		9,72E-03	39	36	31	
2,42E-05	28	25	22		4,95E-03	42	39	34	
2,76E-06	30	27	24		2,15E-03	45	42	37	
1,84E-07	32	29	26		7,72E-04	48	45	40	
6,25E-09	34	31	28		2,17E-04	51	48	43	
9,07E-11	36	33	30		4,50E-05	54	51	46	
4,52E-13	38	35	32		6,35E-06	57	54	49	
5,87E-16	40	37	34		5,54E-07	60	57	52	
1,40E-19	42	39	36		2,63E-08	63	60	55	
3,99E-24	44	41	38		5,85E-10	66	63	58	
7,74E-30	46	43	40		4,97E-12	69	66	61	
5,13E-37	48	45	42		1,27E-14	72	69	64	
4,86E-46	50	47	44		7,06E-18	75	72	67	

We also designed a wireless channel model using MATLAB–Simulink R2013a for power efficiency with comparison of proposed modulation schemes against existing QAM, which is used in LTE/LTE-A networks. We simulated the BER of the proposed schemes and compared it with ordinary QAM schemes.

We provide simulation of 16-QQAM and 64-QQAM with a concerted MIMO scheme, comparing them with ordinary 16-QAM and 64-QAM. Note that 16-QQAM with alternate MIMO has the same BER performance versus energy per bit as 16 QAM. Therefore, we did not simulate this scheme. Simulation results are presented in Table IV.

Fig. 3 shows simulation results of packet loss probability versus symbol energy to noise ratio for 16-ary and 64-ary modulations. Results confirm 5% and 8% gain in energy efficiency for 64-QQAM and 16-QQAMs, respectively.

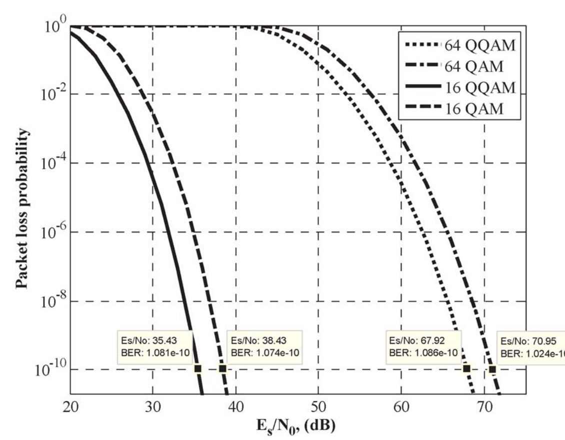

Fig. 3. Packet loss probability comparison for 16-ary modulation for 64-ary modulation.

V. CONCLUSION

We have proposed a new method of quasi-quadrature modulation that transmits only a quadrature component of symbols instead of both quadrature and in-phase components. Our method is compatible with existing quadrature modulation schemes, which are well known and have been used for a long time in LTE mobile networks. We represent digital signal by in-phase and quadrature components, but only one of two symbols are transmitted. This approach can decrease power consumption per symbol transmission with the same bit error probability. We also propose four different schemes of quasi-quadrature modulation using MIMO techniques with different quality-of-service performances, which allowed implementing in CQI-adaptive technique of LTE-Advanced networks. In this paper, we have provided mathematical comparative analysis of energy that is transmitted by eNodeB of an Evolved Universal Terrestrial Radio Access Network. Moreover, we simulated H.264/AVC video transmission through combined NS-2 and MATLAB simulation models. Simulation results confirmed the theoretical analysis. The proposed approach is able to improve energy efficiency by 8% for 16-ary modulation and 5% for 64-ary modulation while providing the same packet loss probability.

REFERENCES

[1] A. Gladisch, C. Lange, and R. Leppla, "Power efficiency of optical versus electronic access networks," in *Proc. 34th Eur. Conf. Exhib. Opt. Commun.*, Brussels, Belgium, Sep. 21–25, 2008, pp. 1–4.

[2] *Report on Climate Change*, Int. Telecommun. Union, Geneva, Switzerland, Oct. 2008.

[3] G. Koutitas and P. Demestichas, "A review of energy efficiency in telecommunication networks," *Telfor J.*, vol. 2, no. 1, pp. 2–7, 2010.

[4] X. Cai, J. Yuan, X. Yuan, W. Zhu, J. Li, C. Li, and S. Ullah, "Energy-efficient relay MAC with dynamic power control in wireless body area networks," *KSII Trans. Internet Inf. Syst.*, vol. 7, no. 7, pp. 1547–1568, Jul. 2013.

[5] A. Saleh, B. Ali, H. Mohamad, M. Rasid, and A. Ismail, "RRSEB: A reliable routing scheme for energy-balancing using a self-adaptive method in wireless sensor networks," *KSII Trans. Internet Inf. Syst.*, vol. 7, no. 7, pp. 1585–1609, Jul. 2013.

[6] "Policy and charging control architecture," Sophia-Antipolis, France, 3GPP TS 36.213 v11.5.0, Release 11, Mar. 2012.

[7] J. Liang, J. Chen, H. Cheng, and Y. Tseng, "An energy-efficient sleep scheduling with QoS consideration in 3GPP LTE-advanced networks for Internet of things," *IEEE J. Emerging Sel. Topics Circuits Syst.*, vol. 3, no. 1, pp. 13–22, Mar. 2013.

[8] B. Stryhalyuk, O. Yaremko, T. Maksymyuk, and O. Melnyk, "Performance increasing method of wireless system based on determining time-frequency localization properties of OFDM signal," *ECONTECHMOD*, vol. 1, no. 3, pp. 49–54, 2012.

[9] M. Klymash, M. Jo, T. Maksymyuk, and I. Beliaiev, "Spectral efficiency increasing of cognitive radio networks," in *Proc. Int. Conf. Exp. Des. Appl. CADSM*, Polyana Svalyava, Ukraine, Feb. 2013, pp. 169–171.

[10] T. Maksymyuk and S. Dumych, "Increasing the spectral efficiency of OFDM signal," in *Proc. Int. Conf. Comput. Sci. Eng.*, Lviv, Ukraine, 2011, pp. 244–245.

[11] T. Maksymyuk, M. Klymash, and M. Jo, "Increasing of energy efficiency of a cognitive radio network," in *Proc. CriMiCo*, Sep. 2013, pp. 277–278.

[12] M. Jo, T. Maksymyuk, M. Kyryk, and L. Han, "Cognitive radio approach for LTE deployment," in *Proc. IEEE Int. Conf. 9th Perspective MEMSTECH Methods Design*, 2013, pp. 63–64.

[13] P. Guskov, R. Kozlovskiy, T. Maksymyuk, and M. Klymash, "Methods and techniques of spectrum refarming for LTE network deployment," in *Proc. CriMiCo*, Sep. 2013, pp. 474–475.

[14] O. Yaremko, B. Stryhalyuk, T. Maksymyuk, O. Lavriv, and D. Kozhurov, "The optimal power control method in multiuser cellular networks," *ECONTECHMOD*, vol. 2, no. 1, pp. 63–67, 2013.

[15] O. Yaremko and T. Maksymyuk, "Power control method in multiuser cellular networks," in *Proc. Int. Conf. Exp. Des. Appl. CADSM*, Polyana Svalyava, Ukraine, Feb. 2013, pp. 386–387.

[16] X. Ge, C. Cao, M. Jo, M. Chen, J. Hu, and I. Humar, "Energy efficiency modelling and analyzing based on multi-cell and multi-antenna cellular networks," *KSII Trans. Internet Inf. Syst.*, vol. 4, no. 4, pp. 560–574, Aug. 2010.

[17] L. Xiang, X. Ge, C.-X. Wang, F. Y. Li, and F. Reichert, "Energy efficiency evaluation of cellular networks based on spatial distributions of traffic load and power consumption," *IEEE Trans. Wireless Commun.*, vol. 12, no. 3, pp. 961–973, Mar. 2013.

[18] W. Stark, H. Wang, A. Worthen, S. Lafortune, and D. Teneketzis, "Low energy wireless communication network design," *IEEE Wireless Commun. Mag.*, vol. 9, no. 4, pp. 60–72, Aug. 2002.

[19] M. Kader, F. Ghani, and R. Badlishah, "Development and performance evaluation of Hierarchical Quadrature Amplitude Modulation (HQAM) for image transmission over wireless channels," in *Proc. Int. Conf. CIMSiM*, Sep. 2011, pp. 227–232.

[20] Q. Fu, D. Qiao, and Y. Li, "Energy-efficient transmission schemes for reed-solomon coded quadrature amplitude modulation," in *Proc. 3rd Int. CISP*, Oct. 2010, vol. 9, pp. 4385–4389.

[21] G. Miao, N. Himayat, G. Li, and S. Talwar, "Low-complexity energy-efficient scheduling for uplink OFDMA," *IEEE Trans. Commun.*, vol. 60, no. 1, pp. 112–120, Jan. 2012.

[22] C. Schurgers, O. Aberthorne, and M. Srivastava, "Modulation scaling for energy aware communication systems," in *Proc. Int. Symp. Low Power Electron. Des.*, 2001, pp. 96–99.

[23] R. Prabhu, B. Daneshrad, and L. Vandenberghe, "Energy minimization of a QAM system," in *Proc. IEEE Wireless Commun. Netw. Conf.*, 2007, pp. 729–734.

[24] I. Lee, J. Hwang, S. Jang, and J. Kim, "Improved resource allocation scheme in LTE femtocell systems based on fractional frequency reuse," *KSII Trans. Internet Inf. Syst.*, vol. 6, no. 9, pp. 2153–2169, Sep. 2012.

[25] L. Lv and Q. Zhu, "Joint relay selection and resource allocation for cooperative OFDMA network," *KSII Trans. Internet Inf. Syst.*, vol. 16, no. 11, pp. 3008–3025, Nov. 2012.

[26] S. Jansen, I. Morita, T. Schenk, and H. Tanaka, "Long-haul transmission of 16×52.5 Gbits/s polarization-division-multiplexed OFDM enabled by MIMO processing," *J. Opt. Netw.*, vol. 7, no. 2, pp. 173–182, Feb. 2008.

[27] T. Maksymyuk and V. Pelishok, "The LTE channel transmission rate increasing," in *Proc. Int. Conf. Mod. Prob. Radio Eng. TCSET*, 2012, pp. 251–252.

[28] L. Han, S. Park, S. Kang, and H. In, "An adaptive FEC mechanism using cross-layer approach to enhance quality of video transmission over 802.11 WLANs," *KSII Trans. Internet Inf. Syst.*, vol. 4, no. 3, pp. 341–357, Jun. 2010.

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