Data-oriented Wireless Transmission for Effective QoS Provision in Future Wireless Systems

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Future wireless systems need to support diverse big data and Internet of Things (IoT) applications with dramatically different quality of service requirements. Novel designs across the protocol stack are required to achieve effective and efficient service provision. In this article, we introduce a novel data oriented approach for the design and analysis of advanced wireless transmission technologies. Unlike conventional channel-oriented approach, we propose to optimally design transmission strategies for individual data transmission sessions, considering both the quality of service requirement and operating environment. The resulting design can effectively satisfy the stringent performance and efficiency requirements of all applications.

1. Introduction
Data is becoming one of the most essential resources of modern society. The timely processing, delivery, and analysis of data will bring huge social and economic benefit. As such, data are being generated and collected at an accelerating rate. In particular, big data applications, such as video surveillance, augmented reality (AR)/virtual reality (VR) gaming and medical imaging, generate data of large sizes. The ever-growing Internet of Things (IoT) devices typically transmit and receive small data packets in a sporadic fashion. The data from different applications also have dramatically different quality of service (QoS) requirements. Certain IoT applications require extremely high reliability and low latency. For example, factory automation applications require a packet loss rate of less than $10^{-9}$ with an end-to-end delay smaller than one millisecond. Other IoT systems involve a huge amount of nodes with seriously limited energy resources. These nodes, usually powered by non-chargeable and non-replaceable battery, are expected to function for over 10 years. Future wireless systems must effectively and efficiently support such machine-type communications (MTC) with diverse QoS requirements.

The development of digital wireless communications over past three decades has been centred on mobile broadband (MBB) service provision. With the deployment of transmission technologies, including channel adaptive transmission, multiple-input-multiple-output (MIMO) transmission and multi-carrier/orthogonal frequency division multiplexing (OFDM) transmission, current generation of cellular and wireless LAN systems can now effectively support the mass offering of MBB services [1,2]. The MBB service can be further enhanced with the application of massive MIMO technology [3] over millimeter Wave (mmWave) frequency range [4] in the emerging fifth generation (5G) cellular systems. Meanwhile, existing technological solutions can not readily satisfy the stringent requirements of future IoT applications in terms of ultra-high reliability, low latency, and very high energy efficiency.

In particular, the latency of current fourth generation (4G) network is in the range of 30-100 ms with the packet transmission reliability of 0.99 [5], which fall way short of the ultra-high-reliability low-latency communications (URLLC) required by mission-critical IoT applications. Several approaches to reduce the latency have been proposed in 5G systems, including virtual network slicing to create private connection for delay reduction over backbone networks [6] and new packet/frame structure with variable numerology to minimize scheduling latency [7]. We need also new technological breakthroughs in physical transmission schemes to effectively satisfy the stringent requirements of critical MTC.

Many IoT applications involve a large number of MTC devices for sensing, metering, and monitoring purposes. These devices will sporadically exchange short packets with less stringent reliability and latency requirements. Meanwhile, the major design challenges for these IoT applications include massive connectivity, wide coverage, low cost, and high energy efficiency. Conventional transmission technologies were designed targeting long data transmission sessions, as required by MBB services, and become highly inefficient in supporting massive MTC [8]. Several possible solutions for scalable support of sporadic short packet transmission are proposed, including minimum signalling/overhead with random access [9], grant-free non-orthogonal access control, and increased base station complexity [10]. Meanwhile, designing highly energy-efficient transmission schemes for massive MTC devices still poses as one of the most fundamental challenge.

To effectively satisfy the stringent performance and efficiency requirements of diverse IoT applications, in this article, we introduce a novel data oriented approach for the design and analysis of advanced wireless transmission technologies for
future wireless systems. Unlike conventional channel-oriented approach, we propose to optimally design the transmission strategies for individual data transmission sessions, considering both the QoS requirements of the data and the prevailing operating environment.

2. Data-oriented Versus Channel-oriented

Conventional wireless transmission technologies were developed while targeting average channel quality, usually characterized by ergodic capacity or average error rate. The general design goal is to enhance and/or approach the effective average data of wireless channels. Typically, the same transmission scheme is applied to all transmission sessions over a wireless link. Following this general channel oriented approach, several transmission technologies [11], such as channel adaptive transmission, multicarrier transmission, multiple antenna transmission, etc., were developed. Generally, these technologies help improve the average quality of the channel, which usually translates to better average QoS experienced by the data. Meanwhile, such channel-oriented approach ignores the specifics of individual data transmission sessions. While the average channel quality indicators can accurately reflect the QoS experienced by long transmission sessions, as in MBB services, they fail to characterize the service quality of short transmission sessions, as illustrated in Figure 1. Note that the QoS experienced by short data transmission sessions varies dramatically with the prevailing channel condition. Such variation will have detrimental effects on the QoS provision for IoT traffics. The channel oriented approach may either cannot deliver the required level of reliability and result in insufficient design for critical MTC or consume too much resource/energy and lead to inefficient implementation for massive MTC.

![Figure 1: Quality of service experienced by long and short data transmission sessions over fading wireless channel.](image)

For example, consider the transmission of a short packet of 1 kB over a wireless channel with average data rate of 10 Mbps and average bit error rate of $10^{-4}$. Can we claim that the packet will be delivered successfully over this channel within 1 millisecond with 99.9999999% certainty? Even if we improve the channel quality to average data rate of 100Mbps and average bit error rate of $10^{-6}$, we will not have a definite answer. The average-channel-quality-based characterization becomes inefficient to determine whether a critical MTC application can be supported.

To effective support IoT application in future wireless systems, we suggest a novel data-oriented approach in the design of wireless transmission technologies. We propose to design and apply transmission strategies from the data’s perspective, instead of targeting the average channel quality. In particular, the transmission strategies are optimally designed for individual data transmission sessions with the consideration of both QoS requirement and operating environment. For a given data packet from mission-critical MTC application, a transmission strategy that minimizes the latency while satisfying the reliability requirement should be applied. Meanwhile, strategies that minimize energy consumption under a certain delay requirement may be used for massive MTC packets. With such design philosophy, different transmission strategies may apply over the same channel for different traffic type. The rationale of such data oriented approach is that optimizing the transmission strategy for individual data sessions will more effectively satisfy the reliability and efficiency requirements, which will in turn enhance the performance of overall transmission system.

A similar design philosophy has been applied in the congestion control of data centres. There are generally two traffic types in data centres: long-lived throughput-sensitive elephant flows and short-lived delay-sensitive mice flows. The elephant flows cause persistent congestions where mice flows create transient congestions. As such, different congestion control policy should apply depending upon the causes of the congestion [12]. While sharing similar philosophy, we propose to apply different physical layer transmission technologies for data with different QoS requirements here.

The design and analysis of wireless transmission technologies with the data-oriented approach typically involves three generic steps. We first need to define suitable performance metrics to quantify the QoS experienced by individual data transmission session. Conventional channel-oriented metrics such as average error rate and ergodic capacity may apply to MBB service, whereas new metrics should be developed for critical MTC and massive MTC. Then, we need to establish the performance limits from individual data transmission session perspective and use them as guidelines for transmission strategy design and optimization. Given the random varying nature of the operating environment, these performance limits should be characterized in a statistical sense. Finally, we can design and optimize practical transmission strategies to approach the established performance limits. Various optimization tools and machine learning algorithms can apply to develop the most favourable transmission strategies for the given operating environment and implementation constraint.

To further illustrate the proposed data-oriented design approach, we present two data-oriented performance metrics, targeting critical MTC and massive MTC, respectively and use them to establish the performance limits for short data transmission. These analysis leads to some brand new insights to wireless transmission system designs.

3. Data-oriented Analysis for Critical MTC

The general design goal of 5G networks for mission-critical IoT applications is to achieve ultra-reliable low-latency transmission. The reliability of digital transmission over wireless channels can be improved with error control coding, retransmission, and diversity combining techniques. Under stringent latency requirement, only coding schemes with short block length may be feasible. Similarly, the latency
requirement will limit the number of retransmission attempts, if any. While diversity techniques demonstrate as the most desirable solution for achieving URLLC, the conventional analysis and design of diversity combining schemes were targeting the average performance metric, such as the average error rate. To effectively satisfy the requirement of URLLC, we need a performance characterization that jointly considers reliability and latency requirements.

To develop a data-oriented performance limits for critical MTC, we raise the following fundamental but not fully answered question: Given a certain amount of data, what is minimum time duration required to successfully transmit it to the destination? The answer to this question will establish the relationship between the best achievable reliability and the corresponding latency requirement and provide important design guidelines for URLLC. Accordingly, we define a data-oriented metric, minimum transmission time (MTT), as the minimum time duration required transmitting a certain amount of data over wireless channels. Let H denote the amount of data to be transmitted. In informational theoretical sense, H represents the amount of information contained in the data. The MTT will be a function of H, denoted by $T_{\text{mtt}}(H)$. For a given H value, MTT will vary with the channel bandwidth, the channel realization, and the adopted transmission strategy. As such, MTT should be characterized in a statistical sense. More specifically, we can define the delay outage rate (DOR) as the probability that MTT for a certain amount of data is greater than threshold duration, denoted by $T_{\text{th}}$. $T_{\text{th}}$ can be related to the latency requirement of the data to be transmitted. As such, DOR serves as a statistical measure for the latency of the data transmission session. For example, we can determine if a factory automation application can be supported by evaluating DOR 1 millisecond and comparing it with $10^{-6}$.

As an application of new data-oriented performance limit DOR, we can compare two classical adaptive transmission schemes for fading channels for the channel state information available at the transmitter (CSIT) scenario, namely optimal rate adaptation (ORA) and optimal power and rate adaptation (OPRA). It has been shown that wireless transmission over fading channel with ORA can achieve the ergodic capacity. It has also been established that OPRA transmission can further enhance the capacity of fading wireless channel with water filling power allocation [11]. Figure 2 compares the DOR performance of ORA and OPRA transmission strategies for small data transmission, where the transmission completes within a channel coherence time, over slow Rayleigh fading channel. In particular, we plot DOR of both strategies as function of the delay threshold $T_{\text{th}}$ for different amount of data. We can see that for both H values, there is a mixed behavior between the DOR performance of ORA and OPRA. Specifically, when the delay threshold is small, OPRA leads to smaller DOR than ORA. When the threshold duration becomes larger, the DOR with ORA transmission improves and becomes much smaller than that with OPRA. In fact, the DOR of OPRA converges to a fixed value when delay threshold becomes very large, which is equal to the probability of no transmission with OPRA.

Figure 3 illustrates the effect of the average received signal-to-noise ratio (SNR) on the DOR performance. We can see that when the average SNR is small, ORA always achieve smaller DOR than OPRA, which holds the transmission with higher probability. When the average SNR increases, the DOR performance of OPRA improves, but still is worse than that of ORA when the delay threshold is large. Note that from the conventional ergodic capacity perspective, OPRA always outperform ORA, especially over low SNR regime. We observe from the DOR analysis, however, that OPRA is not always the better strategy from the perspective of individual data transmission session. OPRA is preferred over ORA when the delay requirement is very stringent or the channel quality is favourable.

4. Data-oriented Analysis for Massive MTC

A typical design goal for massive MTC applications is to achieve the highest possible energy efficiency while satisfying a certain QoS requirement. Existing energy efficiency metrics fail to take into account the reliability requirement of data transmission. To establish suitable data-oriented energy
efficiency limits for individual data transmission sessions, we pose the following fundamental question: What is the minimum amount of energy required to reliably transmit a given amount of data to its destination? The answers to this question will provide the valuable design guidelines for the energy-efficient transmission of big and small data. Accordingly, we define data-oriented energy utilization metric, namely minimum energy consumption (MEC), as the minimum amount of energy required to successfully transmit a certain amount of data over a wireless channel. The MEC will be a function of data amount $H$, denoted by $E_{\text{min}}(H)$. For a given $H$ value, MEC will vary with the transmission power, the channel bandwidth, the channel realization, and the adopted transmission strategy.

Similar to previous section, we can define the energy outage rate (EOR) as the probability that MEC for a certain amount of data is greater than a threshold energy amount. In particular, EOR is mathematically defined as $EOR = \Pr[E_{\text{min}}(H) > E_{\text{th}}]$, where $E_{\text{th}}$ denotes the energy threshold. Equivalently, EOR can be calculated as the probability that the per-bit energy consumption is greater than a threshold value $E_{\text{th}}/H$. As such, EOR serves as a statistical characterization for the energy efficiency experienced by individual data transmission session.

To illustrate further, we study the EOR performance of continuous power adaptation (CPA) over a point-to-point wireless channel that introduces slow flat fading. With CPA, the transmitter adapts the transmission power with the channel condition while maintaining a constant received SNR, denoted by $\gamma_c$ under the peak transmission power constraint $P_{\text{max}}$ (also known as truncated channel inversion [11]). Figure 4 illustrates the EOR performance of CPA over slow Rayleigh fading channels. We can see that maintaining a higher target received SNR with CPA leads to larger EOR. This can be explained by noting that higher $\gamma_c$ implies larger transmission power during transmission on average. We also observe from Figure 4 that larger peak transmission power results in larger EOR, especially when the energy threshold is large. With CPA, larger $P_{\text{max}}$ will lead to larger probability of transmission for the same target SNR. We can conclude that from individual data transmission session perspective, lower power and smaller transmission rate lead to higher energy efficiency.

Figure 5 plots the cumulative distribution function (CDF) of the waiting time before data transmission with CPA over slow Rayleigh fading channels. Note that the delivery time is simply equal to the sum of waiting time and transmission time, which is equal to $H/(\text{Blog}_2(1+\gamma_c))$. We again examine the effect of peak transmission power and target received SNR during transmission. We can see that maintaining a higher target SNR with CPA results in longer waiting time, as intuitively expected. We also observe from Figure 5 that larger peak transmission power helps reduce the waiting time. With CPA, larger $P_{\text{max}}$ will lead to larger probability of transmission for the same target SNR, whereas smaller $P_{\text{max}}$ will ensure that the system transmit only over more favourable channel condition and as such reduce the energy consumption. We conclude that different $\gamma_c/P_{\text{max}}$ values lead to different trade-off between energy efficiency and transmission delay.

5. Concluding Remarks

In this article, we presented a new perspective to wireless transmission technology design, particularly targeting the effective QoS provision in future wireless systems. The data-oriented approach brings interesting new insights to wireless communications. Through the newly proposed data-oriented performance limits, we observe that while OPRA always outperform ORA from the ergodic capacity perspective, OPRA is not always the preferred transmission scheme from the individual data transmission session perspective, especially for critical MTC. We also note that there is a tradeoff of energy efficiency and delay with CPA strategy.

In this article, we illustrated the main idea of the data-oriented approach from the performance metrics definition and performance limit characterization, assuming ideal rate and power adaptive transmission schemes with perfect CSI at the transmitter. There are many directions to further explore the data-oriented approach for wireless system design. In
particular, the practical limited CSI and even non-CSI at the transmitter scenarios are of important practical interest. Adaptive modulation and coding (AMC) and automatic repeat request (ARQ) are two popular transmission strategies that explore limited feedback from the receiver. An initial investigation on the transmission time of a large amount of data with discrete rate adaptation over fading channels has been recently reported [12]. With the established performance limits, we can carry out transmission strategy design and optimization from the data perspective. The general design goal is to arrive at the best transmission strategy for the data to be transmitted over the prevailing channel condition. For example, sophisticated coding and diversity schemes should be invoked for the URLLC transmission, whereas non-coherent energy modulation schemes should be adopted for massive MTC transmission. Given the generally complex channel and interfering condition, the conventional optimization solution based on performance analytical result may not be feasible. Off-line deep learning combined with light-weight on-line reinforcement learning will engender favourable solutions.

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