GREEN MULTIMEDIA WIRELESS SENSOR NETWORKS: DISTRIBUTED INTELLIGENT DATA FUSION, IN-NETWORK PROCESSING, AND OPTIMIZED RESOURCE MANAGEMENT

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ABSTRACT

In developing new applications for green wireless media, power-efficient paradigms and distributed platforms for pervasive sensing, efficient fusion, QoE dissemination, and real-time recovery of multimedia data are of paramount importance. In particular, these topics are challenging in MWSN applications to be compliant with the green wireless media paradigm. In this article, we review the current state of the art in green QoE MWSNs, with reference to mobile users and remote applications. At first, the most relevant aspects regarding the fusion, storage, transmission, and retrieval of multimedia data are reviewed and critically discussed. Afterward, we present some recent paradigms and trends in power-efficient QoE multimedia data fusion and clustering, and collaborative context-aware real-time in-network processing that may serve as guidelines for future green media applications.

INTRODUCTION

Nowadays, supporting green media applications over a system with thousands of independent power-limited sensing devices, all capable of generating and communicating multimedia data in real time, is a key research challenge. A multimedia system of this complexity was unthinkable a few years ago, especially within an energy- and bandwidth-limited failure-prone mobile domain. Today, it is affordable because smartphones, sensors, and actuators can all be connected to the mobile Internet, and every wireless device is capable of generating and disseminating large volumes of multimedia data [1]. Their integration is inherently distributed and ad hoc networking inspired, rather than centrally controlled, provided that it is power-efficient. The aims of this article are to review and outline some recent advances in relevant aspects of this self-evolving distributed system, which involves large-scale distributed multimedia data sources and their clustering, compression, storage, efficient transmission, and retrieval. In fact, while the task of transmitting multimedia information is a common and well understood exercise, the problem of efficiently delivering and sharing, in real time, multimedia information from and among a high number of mobile users and resource-limited devices remains an open issue. In particular, further developments are needed to identify suitable integrated solutions for collaborative signal processing, communication, and distributed resource management in large-scale power-constrained multimedia wireless networked systems.

A multi-tier structure for the considered green multimedia platform is sketched in Fig. 1. The lowest (i.e., first) tier consists of sets of multimedia wireless sensors (MSs), static or mobile, devoted to collecting multimedia information from an environment of interest (EoI). Each set has a local coordinator named a cluster head (CH). CHs are responsible for gathering the information collected by MSs and processing them with suitable multimedia data fusion techniques. The next higher tier is formed by gateways (GWs) that provide connections of the multimedia wireless sensor networks (MWSNs) through the appropriate CHs (first tier) with the content delivery network (highest tier), and hence with remote users and applications. Since MWSNs are usually densely deployed in an EoI, the information flows generated by CHs of adjacent clusters can present spatial correlation. Hence, the green efficiency of the multimedia content delivery network can be improved by removing the resulting redundancy as early as possible in the communication paths toward users and applications. This goal can be achieved by resorting to suitable in-network distributed data compression and coding techniques that lower the amount of data to be delivered without losing information contents.

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Together with issues relating to multimedia information retrieval, compression, storage, and distribution, security is an important additional requirement that is even more challenging due to the multimedia data features in specific applications as in surveillance systems for critical infrastructure environments. With regard to this, a useful survey on security methodologies suitable for use in MWSNs and compliant with the green paradigm (i.e., requiring a limited amount of computational resources and energy) is proposed in [2].

The remaining part of this article is organized as follows. The following section deals with functionalities of the lowest tier of the green multimedia platform shown in Fig. 1, that is, the MWS clustering and intra-MWSN intelligent fusion of multimedia environmental data. The third section deals with efficient distributed compressing and coding methods to face the overlapping of multimedia data generated by nearby CHs, hence avoiding the transmission of unnecessary data. This helps a lot in saving energy and reducing MWSN congestion. Following that we focus on power-efficient delivery (highest tier in Fig. 1) of multimedia data to mobile users and applications over a broadband wireless connection. Then we present an example of a wireless multimedia platform to efficiently support green media applications. Finally, we draw our conclusions.

Power-Efficient Clustering and Intelligent Multi-Sensor Data Fusion

Energy-efficient communication and processing methods are of paramount importance in MWSNs (lowest tier in Fig. 1) due to the massive volume of collected data. As a consequence, in order to allow green wireless media applications, MWSNs have to implement efficient multimedia in-network processing methodologies. Among them, multimedia sensor clustering techniques allow important advantages to multimedia data gathering through MWSNs (randomly) deployed over an area, fully compliant with the emerging paradigm of green media wireless applications. Clustering is usually considered as a specific feature of self-organizing systems and was originally proposed in order to allow specific advantages in terms of energy-efficient connection for wireless communication networks. Two well-known examples of this type of clustering techniques are the low-energy adaptive clustering hierarchy (LEACH) and hybrid energy-efficient distributed clustering (HEED) [3].

Alternative approaches for optimizing cluster forming consider both connectivity properties and semantic information in order to enable capabilities such as multicast queries, intelligent information retrieval, and processing [4]. Recently, approaches to optimizing cluster forming on the basis of game theory methodologies have been also proposed [5]. However, for the MWSNs of interest here, more appropriate methods for optimizing cluster forming are based on application-driven criteria. In particular, for the multimedia green platform of Fig. 1, it is mandatory to perform efficient multi-sensor data fusion (MDF) at the CH level (lowest tier). The scope is to combine different collected data to form higher-quality multimedia information, possibly also reducing the amount of data sent from CHs to GWs, thus enabling energy-efficient communications. According to this methodology, CHs are identified in advance and are devices empowered with specific processing capabilities. Based on context awareness about all the MS features within their communication range, CHs start the clustering forming procedure based on a specific MDF driven criterion, that is, by grouping MSs according to their specific capabilities toward a common goal and avoiding intra-group overlapping. As a consequence, it may happen that the same MS is part of two adjacent clusters formed by nearby CHs, hence giving rise to clusters overlapping (Fig. 2). Solving this problem is a task of the GWs (middle tier in Fig. 1) by means of suitable techniques, discussed in the next section. Nowadays, MDF is an emergent technology based on processing of multimedia data acquired by a network of heterogeneous sensors distributed over an EoI [3, 6]. MDF methodologies effectively combine, merge, and relate with other available multimedia data all the sensed data at different levels.

In the case of distributed MSs and heterogeneous multimedia data, the MWSN can learn from the EoI, and deduce relationships from interconnections and modeling interactions over a specific application domain. An MWSN needs self-organizing capabilities to aggregate MSs into clusters, as discussed before, on the basis of the MDF requirements and goals. The term *intelligence* is often used for these architectures, where intelligence is inherently distributed. In this sense, the MWSN can be considered as a learning machine, getting knowledge from the surrounding environment. CHs are devices equipped with simple local capabilities and able to interface and cooperate with other MSs in order to obtain high global complexity (local simplicity and global complexity). A CH can be

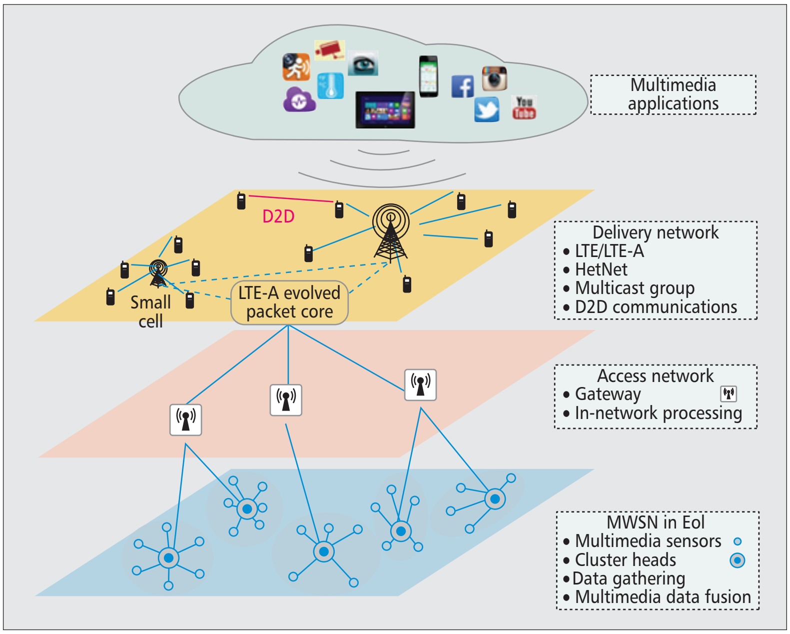

Figure 1. Green multimedia platform architecture.

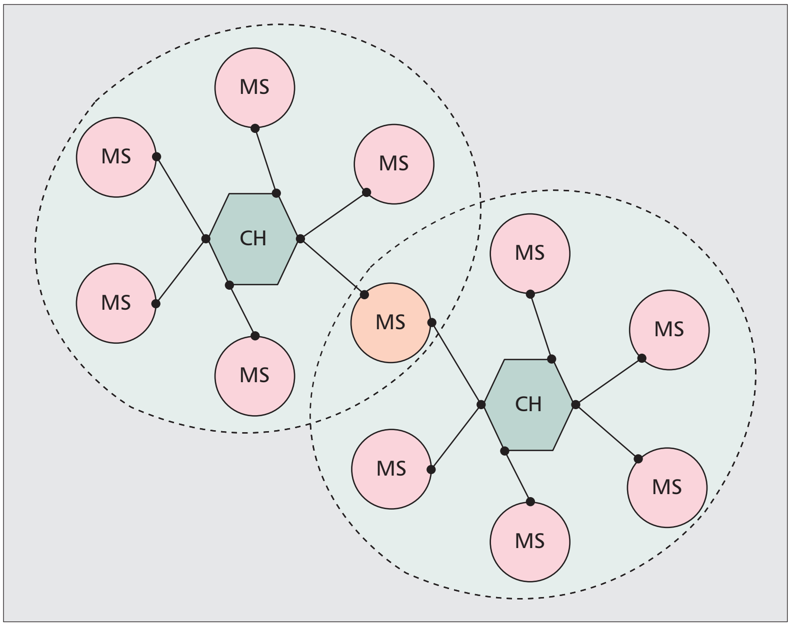

Figure 2. Overlapping clusters.

viewed as an evolved data logger that acquires heterogeneous signals, endowed with the capability of local processing and able to transmit the whole signal or a compressed set of extracted features.

Due to the fact that multimedia data gathered by MSs may be heterogeneous, noisy, incomplete, and displaced by spatial and temporal diversity, it is necessary to develop a systematic approach that allows the autonomous joint optimization of the processing algorithms and computing/communication resources needed for the transmission of the sensed multimedia information. As a consequence, both classical signal processing and advanced computational intelligence and soft computing processing methods are required. Methodologies recast as intelligent signal processing allow adaptive (linear and nonlinear) algorithms to be developed that account for the environmental variability, available signal-to-noise ratio, and fidelity of the sensed multimedia data. Furthermore, feature extraction and classification capabilities have to be envisaged in order to derive and/or aggregate symbolic information to be sent out to GWs.

From an architecture point of view, a general MDF framework should have an elevated abstraction capability in order to allow for the implementation of various data fusion applications. Its performance should be evaluated by adopting novel performance indexes, for instance, algorithm speed vs. error rate (external performance) and multi-tasking operability vs. fusion layers (internal performance) [7].

In-Network Data Compression and Coding

In green media wireless applications, data compression is a primary goal to attain efficient transport and delivery of multimedia data at minimum bandwidth and power costs. Since MWSNs are usually densely deployed over the monitored spatial region, a probable assumption is that the data flows generated by nearby CHs present a certain degree of spatial correlation and redundancy [1]. Obviously, the efficiency of an MWSN is improved by removing spatial correlation and redundancy of multimedia data as early as possible in the communication path toward the final users. This requirement can be fulfilled by resorting to in-network distributed data compression and coding techniques. A classical and well-known technique is the entropy-based compression with explicit message passing approach [1, 8]. However, in the case of the multimedia green platform under consideration (Fig. 1), this method presents the drawbacks of requiring that the underlying spatial correlation pattern has to be known a priori by all the involved CHs and the exchange of a large amount of multimedia data among CHs. More recent and attractive alternatives to performing in-network distributed data compression and coding are the compressive sensing (CS) and joint distributed source coding (JDSC) methods. The CS is an emerging research field in green multimedia data acquisition and processing that bypasses the major drawbacks of the classical data compression and coding methods. Specifically, in the classical data compression and coding methods, environmental signals are first sensed (e.g., acquired) at the Nyquist-Shannon sampling rate, and then compressed for efficient storage and transmission. CS shifts this approach by merging these two processes into a single joint compressive sampling process [1]. The basic concept in the CS paradigm is sparse signals, and the current research on CS focuses on the most efficient (e.g., sparsest) representation and local recovery of sparse signals. Although the growing interest in CS methods has inspired several papers on sensor network data gathering [1], their efficient use in the green multimedia platform sketched in Fig. 1 presents some limitations and open issues that still need to be addressed [9]. In particular, as stated before, CS is effective when the sensed multimedia data are sparse over a suitable transformed domain that, in an actual EoI:

- May depend on the acquired data
- Is not known in advance
- May be difficult to identify online

Furthermore, from a green networking perspective, it is indeed not guaranteed that the transport of CS data is more power- and bandwidth-efficient than the direct transport of data sampled at the usual Nyquist-Shannon rate [1]. Finally, current CS-based algorithms require that each GW recover the overall original data by solving a suitable (generally convex) optimization problem [1] on the basis of the CS data locally computed by each nearby CH.

The JDSC methods aim to optimize source coding without requiring message passing among the encoders; thus, it is capable to maximize both the power and bandwidth efficiency of the underlying transport network [1]. Since distributed source coding, also referred to as Slepian-Wolf (SW) source coding, aims to minimize both processing complexity and communication cost at the source nodes (i.e., CHs) by utilizing spatial correlation information only at the receiving nodes (i.e., GWs), its application is of special interest for green multimedia applications. Different from the CS paradigm, JDSC allows data compression to be decoupled from data transport in order to improve both the power and bandwidth efficiency. Furthermore, this feature of the JDSC paradigm has recently promoted several green media applications. Specifically, by referring to loss data compression in networks with correlated sources and static link capacities, [10] presents a distributed resource allocation algorithm that optimizes routing and coding by allowing the sinks to adjust the corresponding source rates. The final goal of the JDSC scheme of [10] is to maximize an aggregate utility function defined in terms of (tolerated) distortion levels to attain (significant) power savings without hurting the resulting quality of experience (QoE) perceived by the users.

However, direct use of JDSC methods in MWSNs has to be limited to an EoI where the spatial correlation patterns are assumed fixed and known a priori. In particular, this undermines, without suitable countermeasures, their use in applications that require real-time tracking of time-varying contexts or involve mobile devices (i.e., MSs). All these drawbacks can be solved by resorting to a cross-layer resource management engine, as foreseen in the WISENET platform [11] described later. In particular, the cross-layer resource management engine allows the implementation of efficient distributed source and channel coding without requiring message passing between the encoding nodes that dynamically adapts itself to unpredictable context changes due to devices (i.e., MS, CH) failure, modifications of channel propagation conditions, and device mobility.

Green Multimedia Wireless Content Delivery

The continuing growth in demand for multimedia services, mainly for mobile users (MUs) and remote applications, is going to modify the way people and devices comunicate and access information. Furthermore, large and dynamic user communities will want to access multimedia information simultaneously from remote locations and even while mobile. As a consequence, it is mandatory to develop and implement a broadband wireless content delivery network that satisfies all the previous requirements and, in addition, is compliant with the green communication paradigm. To this goal, Long Term Evolution-Advanced (LTE-A) at present seems to be the most promising wireless technology able to efficiently support multimedia content delivery from remote MWSNs to communities of MUs in a multicast/broadcast mode. In particular, we are interested in possible network optimizations and configurations that permit energy saving and, at the same time, guarantee a given level of QoE. LTE-A has a specific framework to provide efficient delivery of multimedia multicast/broadcast services, even across multiple cells, by using the single frequency network (SFN) option. In order to enable green multimedia point-to-multipoint communications, we have to face the drawback that the transmission needs to be adapted to the user under the worst conditions (typically near the cell edge). Without the use of suitable techniques, this leads to high power consumption and typically limits the QoE of the entire multicast group. In this respect, a viable solution offered by LTE-A is to integrate long- and short-range wireless links by using two key technologies of future LTE networks:

- Heterogeneous network (HetNet) deployment
- Proximity communications (see the highest tier in Fig. 1)

Heterogeneous Network

In an LTE-A HetNet deployment several low-power nodes (small cells) are used to integrate traditional macrocell coverage. In general, the use of small cells leads to enhancement of the delivered service quality with increased offered capacity and coverage [12]. But small cells can also be used to reduce the power in transmission (i.e., green communications). In particular, in the reference scenario the LTE-A network is employed to deliver multimedia multicast services to MUs. Exploiting the SFN approach, the same multimedia multicast flow is transmitted simultaneously among different cells over the same working frequency. In this way, depending on the geographical distribution of the MUs and traffic load, it is possible to exploit small cells to save energy and improve the QoE at the MU side. In particular, when the MUs are distributed over a wide area, those close to the cell edge require high transmission power to reach the macrocell base station (BS) and limit the performance of the entire multicast group. Placing the small cells at the edge of the macrocell permits MUs far from the macrocell to adapt their transmit power to the small cell, thus reducing it significantly and improving the QoE of the MUs' multicast group [13]. Small cells can also be used to reach users that are concentrated in a small area, thus avoiding the transmission of the multicast flow in the entire macrocell. This approach becomes more efficient if the cells are managed in an adaptive way. The adoption of power saving protocols could adjust cell size and cell mode (active/idle) depending on the received interference, the traffic load, and the MU distribution to minimize overall power consumption of BSs while maintaining a given QoE at the MU side. To this goal, much attention in the literature is devoted to cell sleeping strategies that permit dynamically activating/deactivating the small cells depending on user activity detection, and cell zooming.

Proximity Communications

In the presence of isolated MUs, even small-cell deployment can be inefficient. However, LTE-A applies another useful technology represented by proximity: device-to-device (D2D) communications.[1] In this case, the multimedia content is distributed to most of the MUs that are in the coverage area of the cells involved in the multicast transmission [14]. Hence, such MUs can exchange this content via cooperation over high-rate short-range wireless links by using direct communication without the need for cellular

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[1] LTE-A also foresees the use of relay nodes, but at the moment this option cannot be used in conjunction with multicast services because they use the same frame structure.

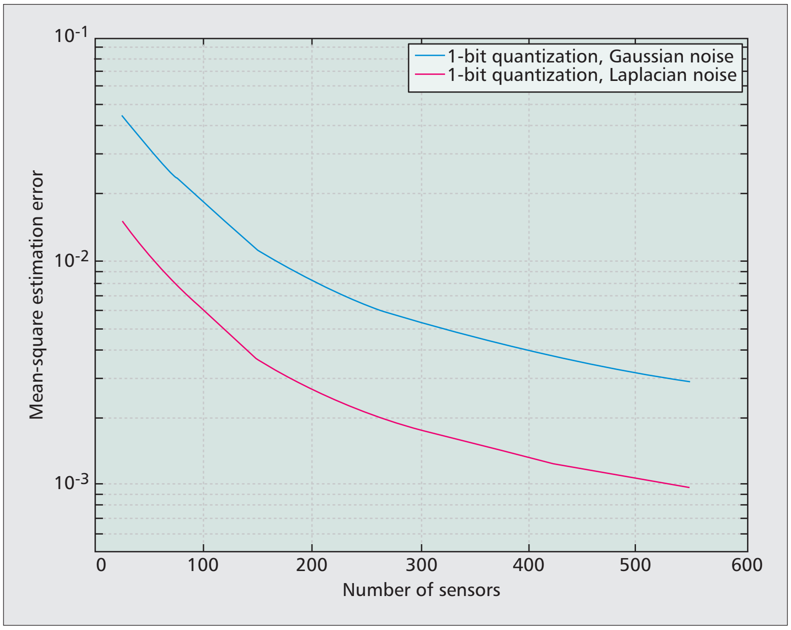

Figure 3. Example of optimal fusion mean square error parameter estimation performance for a dense MWSN assuming 1-bit quantization in the presence of Gaussian or Laplacian noise [6].

network facilities. Indeed, the D2D communication mode permits an MC to be connected with another MU directly using cellular spectrum. Higher rate can be achieved because the nodes involved in the communications are close. In addition, shorter transmission and reception times lead to less energy consumption from the MUs point of view.

A Green Wireless Multimedia Platform Example: The WISENET Paradigm

The research trends outlined in the previous sections have recently converged on the proposal of a wireless multimedia networking paradigm named WISENET [11]. This platform is based on the multi-tier architecture depicted in Fig. 1, and is tailored for managing the multimedia data gathering and proper distribution of green media applications, such as video surveillance, hazard detection, and industrial process control. The main features of the WISENET platform are efficient support of real-time applications with specific service requirements, a functional MWSN implementation that enables the MDF-driven cluster forming technique outlined above, and the use of the JDSC technique outlined previously to reduce power consumption and bandwidth requirement in multimedia content delivery. In particular, the JDSC technique significantly lowers the volume of the data flows delivered by CHs to the appropriate GWs (Fig. 1). Additional important advantages offered by the multi-tier architecture shown in Fig. 1 with respect to alternative solutions (i.e., centralized implementation) are its scalability, robustness to failures, and better performance.

Moreover, MDF performance at the CH level can be enhanced by suitable optimization procedures in order to lower the data to be collected by individual MSs, and hence the bandwidth requirement and energy consumption. As an example, we illustrate in Fig. 3 the results provided in [6]. This figure shows the mean square estimation error performance as a function of the MS number (optimal distribution) under the assumptions of maximum likelihood detection, known noise distribution (i.e., Gaussian or Laplacian), information collected by MSs according to specific local rules and constrained to single-bit quantization.

However, the most important feature of the WISENET platform is the presence of a cross-layer resource management engine that retains four main capabilities. First, it performs, by means of the methodologies outlined above, joint QoE-constrained and optimal distributed source coding, channel coding, and efficient power use. Second, it is amenable to fully distributed, adaptive, and asynchronous implementations, so it is able to cope, by design, with the unpredictable time variations induced by changes in communication channels conditions, device failure, device mobility, and abrupt changes of the underlying spatial correlation patterns [11]. Third, the WISENET resource management engine minimizes, by design, both the power and bandwidth costs, while guaranteeing perfect (e.g., lossless) recovery of multimedia multicast data at the destination MUs. Fourth, the WISENET paradigm allows for heterogeneous multiple sets of client-dependent QoE constraints to be built up and accounted for on a per session basis by suitably combining (typically in a media-dependent way) several objective per-connection service quality indexes: high-fidelity data, packet loss, end-to-end delay, delay-jitter, and the minimum reserved connection bandwidth. As an instance of WISENET performance, Fig. 4 reports the mean power P_{CH} consumed at a tagged CH for data sensing, processing, and transmission when two heterogeneous multicast delay-sensitive media sessions referred to the tagged CH and a nearby one contend for the transport resources toward the same GW. The power curves of Fig. 4 are drawn as a function of ρ, that is, the spatial correlation coefficient between the individual multimedia data flows generated by the tagged CH and the nearby one [11].

In deriving the numerical results shown in Fig. 4, two sensing domains originating two data dissemination sessions have been considered, with different real-time constraints and representing different multimedia sources. In particular, we have assumed a fixed latency maximum values of 20 μs for the multimedia data flow generated by the tagged CH, while different latency target values have been considered for those generated by the nearby CH in order to account for different services such as video surveillance, hazard detection, and industrial processes control. Figure 4 allows us to appreciate the impact of different delay requirements on the resulting mean power consumption at the tagged CH. For comparison purposes, the flat curves report the resulting mean power consumption when no JDSC is performed. Overall, an examination of these curves shows that lowering the maximum per-session end-to-end delay tolerated by the second multimedia flow from 50 μs to 20 μs increases the overall power consumption at the tagged CH side from 0.12 mW to 0.25 mW at $\rho = 0$, and from 0.06 mW to 0.125 mW when ρ approaches unity. Moreover, this figure highlights that, depending on the actual inter-source spatial correlation, halving the per-session tolerated end-to-end delay may result in higher tagged CH power consumption. As stated before, the capability of the WISENET platform to efficiently react to unpredictable context changes enables its use even in the case of mobile devices (i.e., MSs or CHs). More detailed performance investigations that account for link failure, MS/CH mobility, and abrupt changes of the inter-flow correlation ρ are provided in [11]. Finally, it is important to stress that significant performance improvements can be achieved by the use of suitable scheduling methodologies that take into account specific requirements such as multimedia information flows' priority and real-time delivery constraints. With reference to this, an attractive scheduling mechanism is that proposed in [15], which exhibits the important feature of ensuring delivery of different types of data traffic based on their priority and fairness with a minimum latency. Moreover, the proposed scheduling mechanism quickly modifies decisions in response to changes in the application requirements or environment conditions.

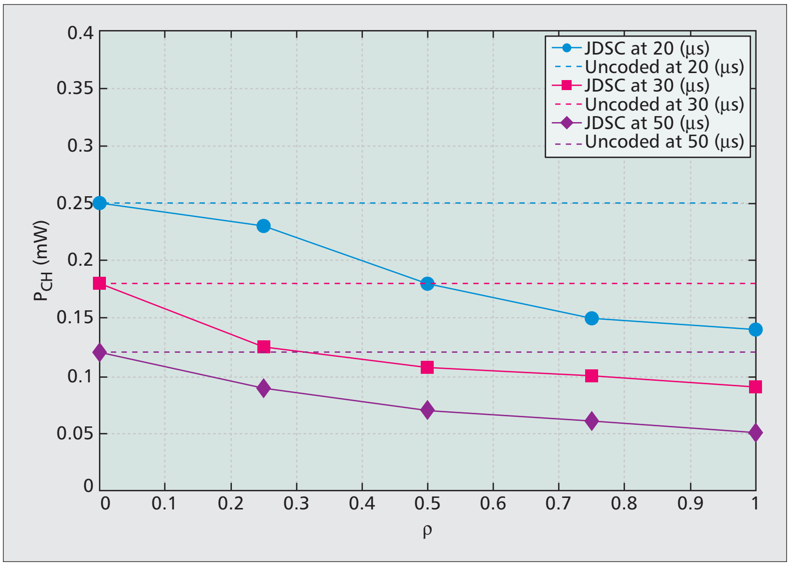

Figure 4. Power saving performance as a function of different inter-flow correlation values.

Conclusions

This article aims to contribute to the advancement of networking technologies for real-time content-aware, distributed, green support of QoE-demanding multimedia services, such as those enabled by the pervasive utilization of Internet-connected mobile MWSNs. Specifically, to support green MWSN-based QoE-demanding multimedia applications over mobile spectrally crowded IP-over-LTE-A connections, we critically review the main technical challenges and state-of-the-art solutions regarding the basic topics of MS clustering, MDF, context-aware in-network collaborative processing, and distributed joint QoE resource management. Finally, as an example of a future green multimedia distributed communication/in-network processing platform, we discuss the salient features of the recently proposed WISENET paradigm, which provides a fully adaptive distributed engine for the QoE asynchronous joint optimization of encoding rates, transmit powers, and transport bandwidths.

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