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COARSE: a cluster-based quality-oriented adaptive radio resource allocation scheme

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Abstract: There is an increasing demand by an ever-growing number of mobile customers for transfer of rich media content. This requires very high bandwidth which either cannot be provided by the current cellular systems or puts pressure on the wireless networks, affecting customer service quality. This study introduces COARSE – a novel cluster-based quality-oriented adaptive radio resource allocation scheme, which dynamically and adaptively manages the radio resources in a cluster-based two-hop multi-cellular network, having a frequency reuse of one. COARSE is a cross-layer approach across physical layer, link layer and the application layer. COARSE gathers data delivery-related information from both physical and link layers and uses it to adjust bandwidth resources among the video streaming end-users. Extensive analysis and simulations show that COARSE enables a controlled trade-off between the physical layer data rate per user and the number of users communicating using a given resource. Significantly, COARSE provides 25–75% improvement in the computed user-perceived video quality compared with that obtained from an equivalent single-hop network.

1 Introduction

Until a couple of years ago, wireless cellular networks carried mostly voice and very little best-effort data traffic. Finally, with the advent of third-generation (3G) mobile systems, increasing popularity of video conferencing and video-intensive applications has put pressure on limited bandwidth resources available. Multimedia transmission and video-on-demand (VoD) streaming require high data rate, which are possible either by requiring higher bandwidth from the network or by having higher received power. As bandwidth is a limited resource in the cellular networks, alternative solutions have to be developed. The very high data rate required for video transmission over wireless networks (i.e. beyond 3G and 4G networks) cannot be offered by the traditional single-hop cellular architecture [1]. This is mainly because of the serious power constraints. For any given transmit power level, the signal energy per bit would decrease with an increase in the transmission rate [2]. As wireless mobile terminals are energy-constrained devices, the terminal transmit power cannot be increased infinitely. To support video transmission over a wide coverage area in a bandwidth constrained wireless network, a fundamental change in the wireless architecture is required. A recent solution has been to incorporate multihop capabilities into the wireless networks [3]. Multihop design not only enables an increase in the data rate, but also increases the bandwidth available to the mobile station (MSs) due to reuse of resources. However, optimum resource allocation in multihop networks is an NP-hard problem [4]. In addition, the deployment costs increase with an increase in the number of hops. Hence, a great amount of focus in recent years has been on two-hop wireless networks [5, 6].

In this context, this paper proposes a novel cross-layer design, COARSE – novel cluster-based quality-oriented adaptive radio resource allocation scheme. COARSE is an adaptive solution spanning across physical layer, link layer and application layer and dynamically adjusts the data rate and the video quality of the multimedia content when delivered over two-hop cellular networks. An adaptive multi-rate system with a trade-off between the number of simultaneously communicating users and the video quality offered to each user is developed in COARSE. The data rate and consequently the offered video quality are varied in accordance with a carrier-to-interference ratio threshold that could be dynamically set in the system.

The organisation of this paper is as follows: Section 2 summarises related works in multihop design and quality-oriented adaptive scheme. Section 3 describes COARSE in detail. The simulation model, different scenarios, numerical and simulated testing results are presented in Section 4. The paper ends with Section 5 that talks about the conclusions and future research in this direction.

2 Related works

Recently, there has been significant amount of work done in multihop cellular networks (MCNs) as a next generation wireless architecture, because of its enormous potential to boost the cellular system capacity and coverage while at the same time reducing the transmission range of mobile devices [7, 8]. However, this is still a nascent field with many open research areas. Air-interface design, scheduling and radio resource allocation techniques are some of the most prominent research topics in this field.

In the multihop architecture for cellular communications, the source and destination nodes communicate with each other over multiple hops [9]. Different algorithms and architectures have been proposed over the recent years for efficient spectrum and resource utilisation in MCNs [10, 8]. An integrated cellular *ad hoc* relay network has been proposed in [11] that diverts the traffic from highly loaded cells to lightly loaded cells. Furthermore, a multihop cellular hybrid architecture, mobile-assisted data forwarding has been investigated in [12] wherein, the multihop is overlaid on the wireless cellular networks, to adaptively change the traffic from a densely used cell to a sparsely used cell. Similarly, a multihop design is studied in detail in [13–15] where the end-to-end communication is always between the MS and Base Station (BS) like in a traditional single-hop cellular network. There has been considerable research work in finding different routing techniques for MCNs, viz., base-assisted *ad hoc* routing, base-driven multihop bridge routing [16] single-interface MCN routing protocol [17], for different kinds of traffic patterns. These techniques effectively use the *ad hoc* relaying in presence of fixed infrastructure to achieve enhanced network capacity. Jetcheva *et al.* [18] conducted practical experiments around Washington, DC in the USA and showed that 84% of multihop communication takes place within four hops, with 62% of the communication happening in two hops. Hence, researchers across the world have mainly focused on two-hop cellular networks [19]. In a significant piece of work, Grossglauser and Tse [20] proved that with a proper design, mobility actually increases the capacity of a two-hop cellular network.

There are three main issues currently researched in next generation multihop networks:

1. New mechanisms to increase system spectral efficiency [21].
2. Solutions to dynamically choose between serving high number of users with a moderate data rate and limited number of users with high data rate [22].
3. High-quality personalised video services [23].

With an increase in the demand for multimedia streaming in wireless networks, there have been several approaches researched in the recent past. Transport friendly rate control protocol (TFRCP) is a unicast transport layer protocol, designed for multimedia streaming, and provides nearly the same amount of throughput as that of Transport Control Protocol (TCP) on wired networks. The TFRCP controls rate based on network conditions expressed in terms of round trip time (RTT) and packet loss probability [24]. Similar to TFRCP, enhanced loss delay adaptation (LDA+) also aims to regulate the transmission behaviour of multimedia transmitters in accordance with the network congestion state [25]. LDA+ uses real-time transport protocol for calculating loss and delay and uses them for regulating transmission rates of the senders. LDA+ adapts the streams in a manner similar to that of TCP connections. In comparison, receiver based auto rate (RBAR) is a receiver-based auto-rate mechanism. It is a medium access control layer protocol and is based on RTS/CTS mechanism [26]. The main feature of RBAR is that both channel quality estimation and rate selection mechanism are on the receiver side. However, none of the solutions propose a concrete solution, spanning across several layers. In their landmark paper, Van der Schaar and Shankar [27] have explained the different challenges, opportunities and new paradigms in the cross-layer design for wireless multimedia. Different cross-layer-based solutions for multicast video streaming have been studied in [28, 29]. However, to the best knowledge of the authors, none of the existing mechanisms provide an integrated solution.

In this context, COARSE aims to provide a novel architecture-oriented integrated solution satisfying all three issues mentioned above. COARSE is a cross-layer design approach with a focus on the lower layers and is complementary to the previous research work on adaptive scheme performed at the application and transport layers – quality oriented adaptive scheme (QOAS). Following the findings on QOAS in [30], a cross-layer approach spanning upper and lower layers was found to be very important to perform quality-oriented adaptation.

3 Cluster-based quality oriented adaptive radio resource scheme

3.1 Network architecture

A multihop design facilitates simultaneous use of the radio resource which in turn results in considerable interference. To analyse the effect of this interference, Gupta and Kumar [31] introduced two kinds of interference models: protocol model and physical model. A state-of-the-art hierarchical cluster-based design for two-hop cellular networks has been recently proposed in [32] under the protocol interference model. In this design, the given radio resource is reused in every cell in the multi-cell scenario. A schematic of the design is shown in Fig. 1*a*. In this design, the hexagonal cell with a side length (r) is divided into two regions: inner region and outer region. The outer region is divided into several clusters. Each cluster has a cluster-head node, also known as gateway (GTW). All the GTWs in each cell are equidistant from each other and located at the boundary separating the inner region and outer region, as shown in Fig. 1*b*. To satisfy this cluster-based design, the number of clusters, and hence, the number of GTWs in a cell has to be an even number [32]. The BS first communicates with the GTW, which then communicates with the MSs as shown in Figs. 1*b* and *c*, respectively. In this context, the maximum transmission distance of a pair is $r/2$. It should be noted at this stage that in reality, the cells would not be exactly hexagonal in nature. However, this does not change the principle of the cluster-based mechanism. A time division duplexing (TDD)/time division multiple access system is considered in the COARSE system design, whereby a time slot is considered to be a radio resource [33]. At any time instant, there are two concurrently communicating pairs at diametrically opposite locations of a cell with respect to the BS, as can be observed from Figs. 1*d* and *e*. Hence, the frequency reuse of the cluster-based two-hop cellular network is one, that is every cell has two pairs that uses the same radio resource.

The cluster-based design has been originally proposed under the protocol model [32]. However, its main disadvantage is that it does not take into account the cumulative effect of the interference because of the concurrently communicating pairs in the system. This results in a non-realistic interference analysis. Hence, in this paper, a physical interference model is considered. A significant benefit of using the physical model for real-time

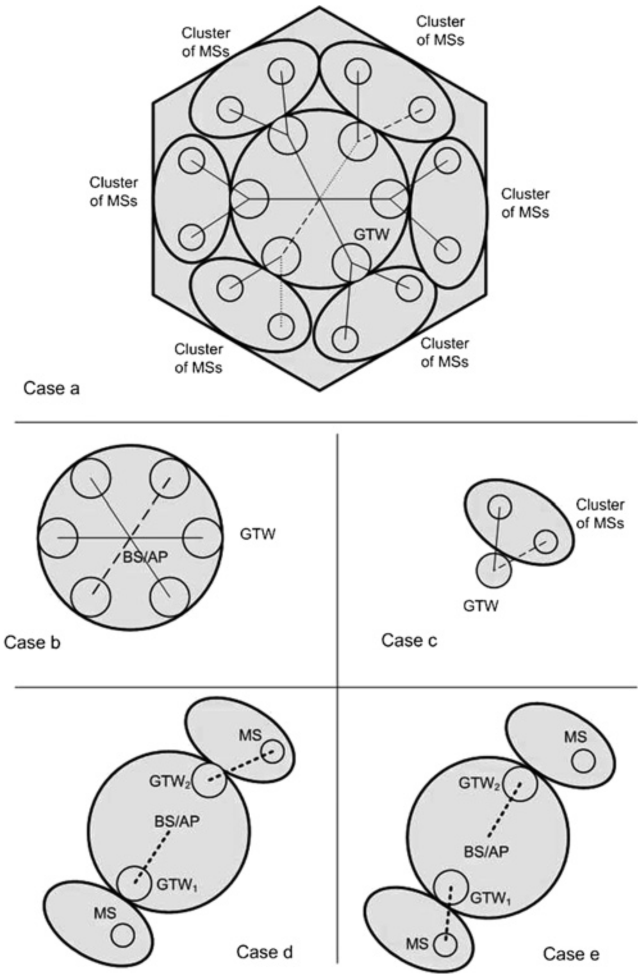

Fig. 1 *Two-hop cluster-based cellular architecture*

interference calculation is that the *C*/*I* experienced at the intended receiver is a function of the number of simultaneously communicating pairs and the distance of the interfering transmitters. The main disadvantage of using physical modelling till a couple of years back was that it was supposed to be computationally more intensive than protocol modelling. However, with better digital signal processing techniques and improvements in very large scale integration (VLSI) design, this reason does not hold much significance in present times.

An adaptive transmission scheme is implemented in the cluster-based two-hop networks by adaptively selecting the modulation technique, depending on the *C*/*I* at the receiver. The COARSE server is placed at the mobile switching centre (MSC), which controls all the BSs. The server then calculates the modulation technique and the number of simultaneously communicating pairs in the network depending on the *C*/*I* experienced by each communicating receiver and the data rate demand of different users. In the next subsection, the theoretical calculation of *C*/*I* is presented along with the cross-layered adaptive scheme.

3.2 Theoretical calculation – C/I

Most multimedia streaming and video transmissions in particular are in downlink direction. Hence, the analysis of COARSE also focuses on the downlink mode only. Fig. 2 shows a multi-cellular model for two-hop transmission. There is a MSC at the centre of network, which controls all the BSs in its vicinity (centre cell, first tier, second tier and so on). All the wireless terminals in any cell are assumed to transmit their signals with the same power, P_T. If d_c is the transmission distance between any communicating pair, then the power received, P_R, using a general propagation model is given by

$$P_R = P_T - \{k_1 + 10\alpha \log_{10}(d_c) + \zeta_c\}\,(\text{dB}) \qquad (1)$$

where k_1 is a constant that depends on the propagation environment (indoor/urban/suburban), α is the path loss exponent and ζ_c is the shadowing factor across the transceiving pair. The interference is calculated at the GTW node in the centre cell from all possible interfering transmitters from own cell, first tier and second tier cells. The carrier-to-interference ratio at the receiver of a communicating pair of user is therefore calculated as follows:

$$\frac{C}{I} = \frac{10^{-\{k_1+10\alpha\log_{10}(d_c)+\zeta_c\}}}{\sum_{i=1}^{N_I} 10^{-\{k_1+10\alpha\log_{10}(d_i)+\zeta_i\}}} \qquad (2)$$

where d_i is the distance of the desired receiver from the *i*th interfering entity and N_I is the total number of interfering entities for any receiver in a cluster-based model. ζ_i accounts for shadowing between the desired receiver and the *i*th interfering transmitter. For the mathematical analysis, two cells are considered: cell 0 and cell 1. The lognormal shadowing factor, ζ is considered to be zero. As shown in Fig. 3*a*, the distance of receiving GTW at cell 0, GTW_{1a}, from the BS of cell 1 is given by

$$d_{BS_1} = \sqrt{\{2\sqrt{3}d_c - d_c\cos(q_{11})\}^2 + \{d_c\sin(q_{11})\}^2} \qquad (3)$$

whereas the distance of the unintended transmitting GTW of the cell 1, GTW_{2b}, to the desired GTW receiver in cell 0,

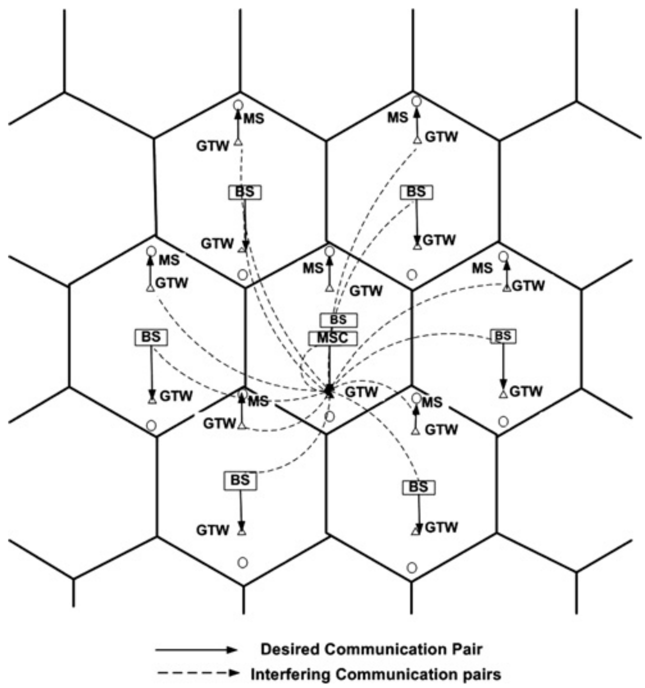

Fig. 2 *Interference at the gateway node of centre cell*

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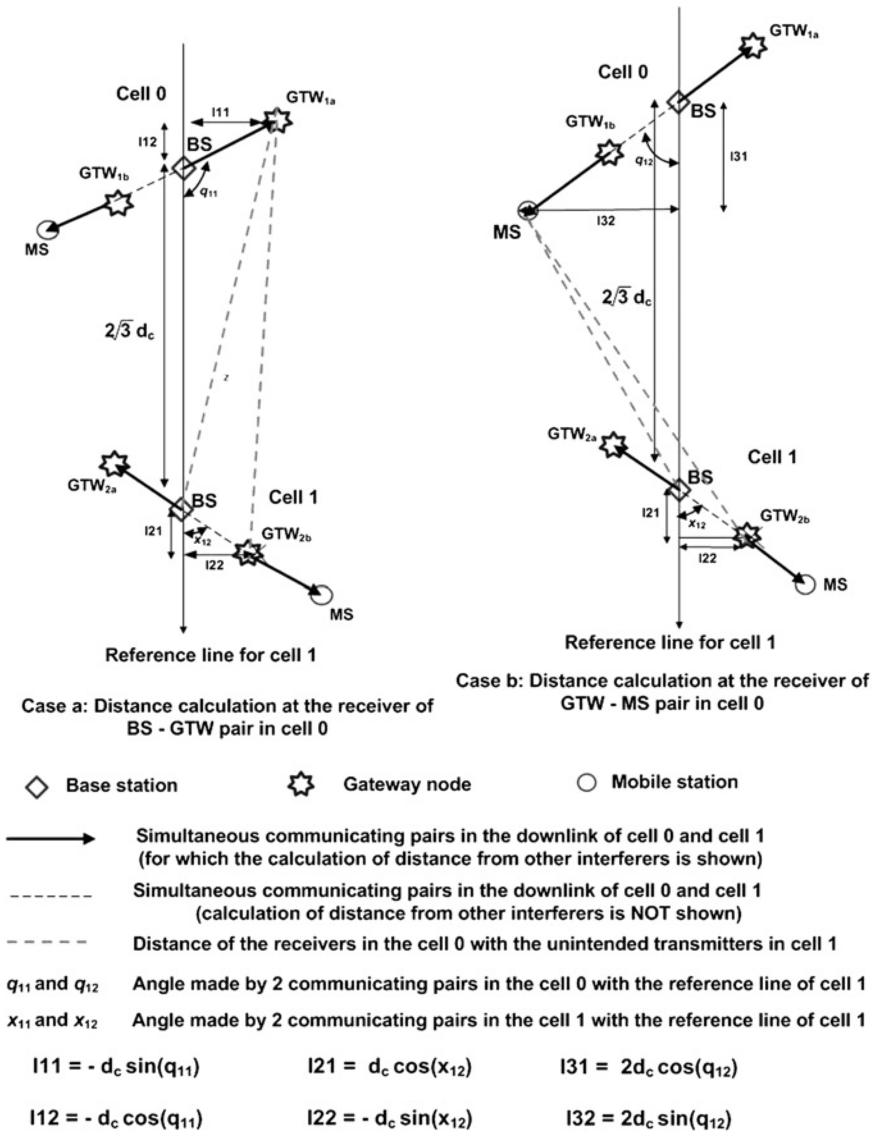

Fig. 3 *Distance calculation at the receivers of BS → GTW and GTW → MS pairs*

GTW_{1a}, is given by

$$d_{GTW_1} = \sqrt{d_{GX_1}^2 + d_{GY_1}^2} \quad (4)$$

where

$$d_{GX_1} = 2\sqrt{3}d_c + d_c\cos(x_{12}) - d_c\cos(q_{11}) \quad (5)$$

$$d_{GY_1} = d_c\sin(x_{12}) - d_c\sin(q_{11}) \quad (6)$$

The angle, q_{11}, is formed between the line joining the communicating pairs, $BS \rightarrow GTW_{1a}$ in cell 0 with the reference line of cell 1. Similarly, x_{12} is the angle between the line joining the communicating pairs, $GTW_{2b} \rightarrow MS$ in cell 1, with the reference line of cell 1. Equations (3) and (4) could be generalised to calculate the interference coming from the transmitters of any other cells into the desired receiver (i.e. GTW of intended cell). By changing the reference line for each of the adjacent cells in a particular tier, the distance of the interfering transmitters from the *i*th cell in *j*th tier is written as

$$d_{BS_i} = \sqrt{\{p_j - d_c\cos(\theta_{i1})\}^2 + \{d_c\sin(\theta_{i1})\}^2} \quad (7)$$

whereas the distance of the interfering transmitter to the desired GTW receiver is given by

$$d_{GTW_i} = \sqrt{d_{GX_i}^2 + d_{GY_i}^2} \quad (8)$$

where

$$d_{GX_i} = 2\sqrt{3}d_c + d_c\cos(\phi_{i2}) - d_c\cos(\theta_{i1})$$
$$d_{GY_i} = d_c\sin(\phi_{i2}) - d_c\sin(\theta_{i1})$$

Here, the value of p_j is the distance between the BS of the centre cell and the BS of a cell across the *j*th tier. Hence, in case of first tier, the value of p_1 is $2\sqrt{3}d_c$, whereas in case of interference across the second tier, third tier and further, the value of p_1 is $6d_c$, $6\sqrt{3}d_c$ and so on. Similarly, the angle θ_{i1} made by the $BS \rightarrow GTW$ communicating pair in the intended cell with the reference line of ith cell in jth tier is given by

$$\theta_{i1} = q_{i1} + \frac{360}{6 \times j}(i-1) \quad (9)$$

and

$$\phi_{i2} = x_{i2} + \frac{360}{6 \times j}(i-1) \quad (10)$$

is the angle in degrees made by the GTW → MS in the ith cell with the reference line of the ith cell (Fig. 3a shows the angle x_{12} made by the GTW_{2b} → MS communicating pair in cell 1, with the reference line of cell 1). It should be noted that θ and ϕ vary uniformly from [0°, 360°]. In addition, the distance of intra-cell interfering transmitter is, $d_{\text{owncell}} = 2d_c$. The C/I value at the receiver of any communication pair is therefore given by

$$\frac{C}{I} = \frac{d_c^{-\alpha}}{(2d_c)^{-\alpha} + \sum_{i=1}^{X} \{d_{(\text{GTW})_i}\}^{-\alpha} + \sum_{i=1}^{Y} \{d_{(\text{BS})_i}\}^{-\alpha}} \quad (11)$$

where X is the number of cells considered wherein the GTW → MS pair communicates at the same instant as the pairs in centre cell. Similarly, Y indicates the number of adjacent cells wherein the BS → MS pair communicates at the same instant as the intended user in centre cell. Dividing by $d_c^{-\alpha}$ results in

$$\frac{C}{I} = \frac{1}{2^{-\alpha} + \sum_{i=1}^{X} \{\kappa_{(\text{GTW})_i}\}^{-\alpha} + \sum_{i=1}^{Y} \{\kappa_{(\text{BS})_i}\}^{-\alpha}} \quad (12)$$

where

$$\kappa_{(\text{BS})_i} = \sqrt{13 - 4\sqrt{3}\cos(\theta_{i1})}$$

$$\kappa_{(\text{GTW})_i} = \sqrt{14 + 4\sqrt{3}\{\cos(\phi_{i2}) - \cos(\theta_{i1})\} - 2\cos(\zeta_i)}$$

and

$$\zeta_i = \phi_{i2} - \theta_{i1}$$

For the seven-cell scenario

$$0 \le X \le 6 \quad \text{and} \quad 0 \le Y \le 6$$

whereas, for 19-cell scenario

$$0 \le X \le 18 \quad \text{and} \quad 0 \le Y \le 18$$

3.3 System architecture and COARSE working mechanism

Fig. 4 presents the client–server architecture. The MSC acts as COARSE server and BSs/GTWs as the clients. Multimedia data are distributed between the BSs/GTWs and the MSs in the individual cells via the state-of-the-art adaptive solution, QOAS [30]. COARSE relies on the fact that a given radio resource could be used by several users if the C/I experienced by each user is above a certain threshold. This threshold, β, is set dynamically by the MSC depending on the current network traffic, bit-error-rate and

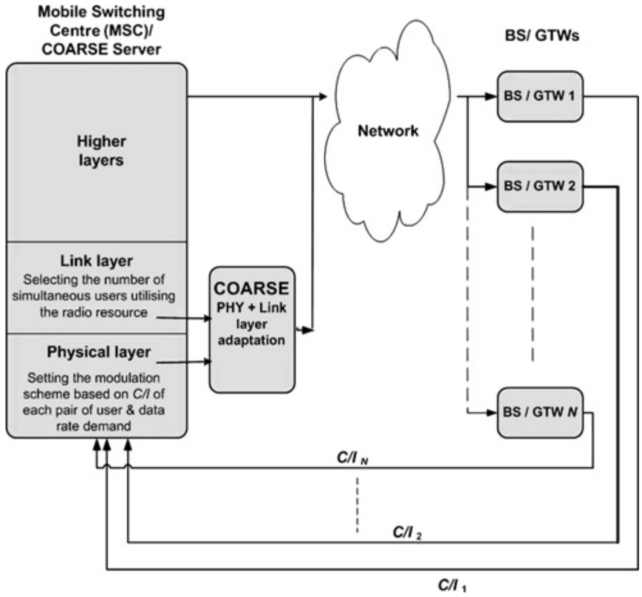

Fig. 4 *Cross-layer design at the MSC acting as COARSE server*

the data rate demand of different users. Depending on the number of users and the received C/I values from individual BSs, the COARSE server selects the β value and sends this information to all the BSs. A higher modulation technique implies a higher number of bits/symbol which in-turn increases the data rate and thereby the video quality of the transmission. On similar lines, if the traffic load for video transmission is high and the system demand is to serve high number of users, value of β is then reduced by the MSC. A lower modulation technique is used in the physical layer resulting in a reduction in the data rate and a subsequent reduction in the video quality offered to each user. Of note, an uncoded system with a BER of 10^{-2} is considered in this work. This is because, in reality, with a combination of convolutional/Reed-Solomon coding techniques, the uncoded BER of 10^{-2} translates into a BER of 10^{-6} or beyond, in a coded system.

It can be seen from Table 1 that for a BER of 10^{-2}, the minimum C/I required in a Gaussian fading channel for a simple binary phase shift keying (BPSK) modulation technique is 4.6 dB. The minimum C/I required for using quadrature phase shift keying (QPSK) scheme is 7.1 dB. Hence, for a C/I from 4.6 dB up to 7.1 dB, only 1 bit/symbol could be transmitted, which in-turn results in a lowest possible data rate for a given bandwidth [34]. With an increase in the received C/I, COARSE could use a higher C/I threshold, which would enable transmission of larger number of bits per symbol. For example, for a C/I of 18 dB, a 32QAM modulation scheme could be used at the physical

Table 1 Minimum C/I for an uncoded system with a BER of 10^{-2}

Type of modulation	C/I threshold, dB	Number of bits/symbol
BPSK	4.6	1
QPSK	7.1	2
8PSK	11.3	3
16QAM	14.2	4
32QAM	17.4	5
64QAM	19.6	6
128QAM	22.4	7
256QAM	25.2	8
512QAM	28.4	9

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layer, which would result in five times the transmission rate as compared with the case when the C/I threshold is 6 dB, for which only BPSK modulation scheme could be used.

4 Performance analysis and testing

4.1 Testing setup and scenarios

To assess the performance of COARSE, a seven-cell scenario is considered over a coverage area of 1 km^2. Each cell is allocated a bandwidth of 1.5 MHz. Thousand MSs are assumed to be uniformly distributed across the coverage area. Each cell is divided into inner region and outer region. The outer region is divided into six clusters. Each cluster has a fixed cluster-head (i.e. GTW), located at the boundary of inner region and outer region of the cell. For such an environment, which illustrates an airport or a corporate/university campus, the propagation constant, k_1, is set to 37 and the path loss exponent, α, to be 4. In addition, a lognormal shadowing component with zero mean and a standard deviation of 4 dB [35] is considered. The system is interference limited, so the total interference is much greater than noise. Hence, no noise is being considered in the simulations.

To analyse the effect of resource allocation and data rate variation of COARSE, the network is modelled and simulated using Matlab, as carried out in [33]. This is because Matlab provides excellent features to incorporate both physical layer and link layer characteristics in the network design. However, the biggest disadvantage is to make application level changes using Matlab. Hence, once the architecture of COARSE was designed and tested using Matlab, another simulation software was used, to calculate the video quality experienced by the end-users. This is done by remodelling the cluster-based two-hop hierarchical design using the server–client model instances in network simulator, version 2.31 (NS2). The main advantage of using NS2 is that it models not only the network layer and application layer, but also takes into consideration the parameters from physical layer and link layer. NS2 simulation is done at the packet level and the performance is analysed in terms of the calculated user perceived quality. Given the complexity of the network, a two-tool simulation approach enabled a thorough evaluation of the cross-layer design.

Following the recommendations from the ITU-T R. P.910 standard [36], a five-state scale is considered for multimedia streaming process. At the media access control layer, an IEEE 802.11-based distributed coordination function is used. A user datagram protocol is considered for transmission and the content is encoded using MPEG4. The length of the simulations is kept at 200 s. The traffic used in this paper was generated by encoding a movie from a television channel, at a frame rate of 30 frames/s and using a group of picture pattern with 9 frames/group of picture between intra-coded I frames and three frames in between two successive predictive coded P frames [37]. Assessment is performed in terms of no reference moving picture quality metric, Q, which is calculated on 1–5 grading scale [38].

4.2 Theoretical results for C/I

This paper considers interference from own cell and across the first tier of cells only. The number of pairs communicating simultaneously using the same radio resource vary from 0 to 2, both in the centre cell and in each of the adjacent cells. Two separate cases are discussed, depending on the number of simultaneously communicating pairs in the cell of interest (CoI):

1. The CoI has two simultaneously communicating pairs.
2. The CoI has only one simultaneously communicating pair.

To analyse the behaviour of the C/I experienced at the receiver of the BS $\rightarrow$ GTW communication in the CoI, all possible positions of the GTWs in the adjacent cells are considered and for each possible position, the interference and C/I are computed. The minimum value for C/I is obtained by considering the minimum distance of the inter-cell interfering entities. It can be observed from Fig. 3 that the minimum distance of the interfering transmitters (BS/GTW) from the adjacent cells are $d_{BS} = \sqrt{3}r - r/2 \simeq 1.232r$, and $d_{GTW} = \sqrt{3}r - r \simeq 0.732r$, respectively. Similarly, the maximum distance of the interfering entities are $d_{BS} = \sqrt{3}r + r/2 \simeq 2.232r$, and $d_{GTW} = \sqrt{3}r + r \simeq 2.732r$, respectively. The minimum and maximum distance of the interfering transmitters from other cells are calculated in a similar way by simply changing the orientation of the reference line.

1. *Two simultaneously communicating pairs in CoI*: The total number of interferers (intra-cell + first tier) vary between 2 and 14. The C/I ratio in this case is therefore given by (11). Table 3 shows the variation of minimum and maximum C/I per pair with the number of communicating pairs, that is from 2 to 14.

Table 2 *C/I* variation and COARSE-assigned modulation technique when CoI has two simultaneously communicating pairs

Number of pairs	C/I_{min}, dB	C/I_{max}, dB	Possible modulation scheme	Highest scheme
2	11.04	22.1	QPSK/64QAM	64QAM
3	10.47	19.9	QPSK/64QAM	64QAM
4	9.85	18.7	QPSK/32QAM	32QAM
5	9.52	16.8	QPSK/16QAM	16QAM
6	9.37	14.62	QPSK/16QAM	16QAM
7	8.94	12.86	QPSK/8PSK	8PSK
8	8.65	11.4	QPSK/8PSK	8PSK
9	7.12	10.65	QPSK	QPSK
10	5.56	9.82	BPSK/QPSK	QPSK
11	5.44	8.6	BPSK/QPSK	QPSK
12	5.41	7.3	BPSK/QPSK	QPSK
13	5.38	6.2	BPSK	BPSK
14	4.72	5.1	BPSK	BPSK

Table 3 *C/I* variation and COARSE assigned modulation technique when CoI has only one communicating pair

Number of pairs	C/I_{min}, dB	C/I_{max}, dB	Possible modulation scheme	Highest scheme
2	15.66	25.98	16QAM to 256QAM	256QAM
3	13.89	22.7	8PSK/16QAM to 128QAM	128QAM
4	13.08	20.04	8PSK/16QAM to 64QAM	64QAM
5	12.75	17.61	8PSK/16QAM & 32QAM	32QAM
6	12.47	14.96	8PSK/16QAM	16QAM
7	9.29	12.35	QPSK/8PSK	8PSK
8	7.16	11.93	QPSK/8PSK	8PSK
9	6.67	11.38	BPSK/QPSK	8PSK
10	6.51	10.65	BPSK/QPSK	QPSK
11	6.47	10.06	BPSK/QPSK	QPSK
12	6.41	7.89	BPSK/QPSK	QPSK
13	5.36	6.92	BPSK	BPSK

2. *One communicating pair in CoI*: In this situation, the total number of interfering entities vary between 1 pair and 13 pairs. Therefore the expression for C/I in case of single communicating pair in CoI is given by

$$\frac{C}{I} = \frac{d_{\mathrm{c}}^{-\alpha}}{\sum_{i=1}^{X} (d_{(\mathrm{GTW})_i})^{-\alpha} + \sum_{i=1}^{Y} (d_{(\mathrm{BS})_i})^{-\alpha}} \qquad (13)$$

The only difference between (11) and (13) is that (13) does not have intra-cell interferer. Table 2 shows the theoretical minimum and maximum C/I values when the number of simultaneously communicating interferers vary from 1 to 12. By comparing Tables 2 and 3, it can be derived that the interference is relatively higher in case of two communicating pairs in CoI, as compared with when there is only one pair using the radio resource in centre cell.

4.3 Simulation results

Fig. 5 shows the variation of the average data rate per user for increasing C/I ratio values. It can be observed that for low C/I values, the data rate per user is very less. With an increase in C/I, the data rate served by a user increases. For example, for a C/I threshold of 20 dB, the data rate of the users is 780 kbps in case of two users in CoI and 920 kbps in case of one user in CoI. Of note, the data rate per user, for a C/I of 20 dB, in case of a single-hop network is only 320 kbps, atleast 2.5 times less than that obtained from COARSE. Significantly, for a low value of C/I threshold, for example 10 dB, the data rate per user obtained under COARSE is around 300 kbps (for both one and two users in the CoI), whereas the data rate of a single-hop network is 32 kbps, almost ten times less than that obtained from COARSE.

Fig. 6 shows the average data rate per user when the number of simultaneously communicating users using a given radio resource in the system is varied from minimum-to-maximum value. When the number of communicating pairs is increased, the average data rate goes down. This is because the C/I threshold and thereby, the selected modulation technique is reduced. In addition, for the same number of users, the average data rate in case of two users in the centre cell is lower than when there is only one user in the centre cell. This is because, when there are two

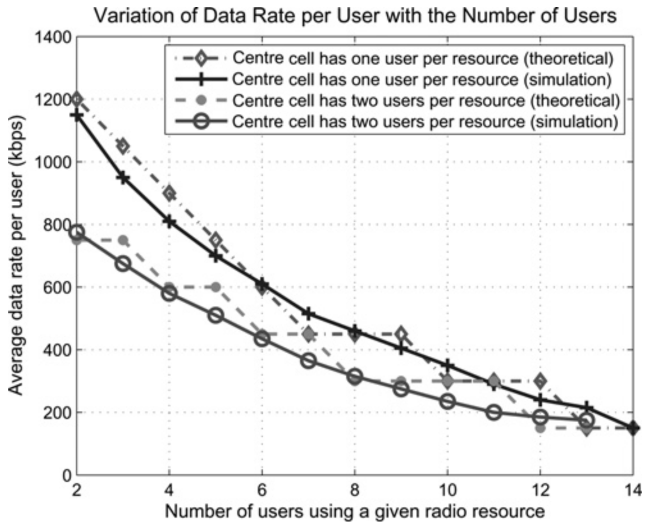

Fig. 6 *Variation of data rate per user with varying number of users*

simultaneously communicating users in the centre cell, the interference is higher which in-turn reduces the data rate per user. Of note, in Fig. 6, there is a close match between the theoretical and simulation results. The minor difference is because the simulation results is obtained by averaging over all possible combinations for a given number of simultaneously communicating users in the network. Hence, the graph obtained is a smooth curve. In addition, a lognormal shadowing with a standard deviation of 4 dB is considered in the simulation, which is not considered in the theoretical analysis.

Fig. 7 shows the calculated video quality, Q, of the users when the number of simultaneously communicating users is varied in the seven-cell network. Using COARSE, the streamed video quality decreases almost linearly in a controlled manner, with an increase in the number of users. This holds true irrespective of whether there are one or two users in the centre cell. With only seven users in the seven-cell network, the average perceived quality is found to be 3.9 and 4.51 for one user and two users in the centre cell, respectively. With all the 14 users in the network communicating simultaneously, the average Q per user is 3

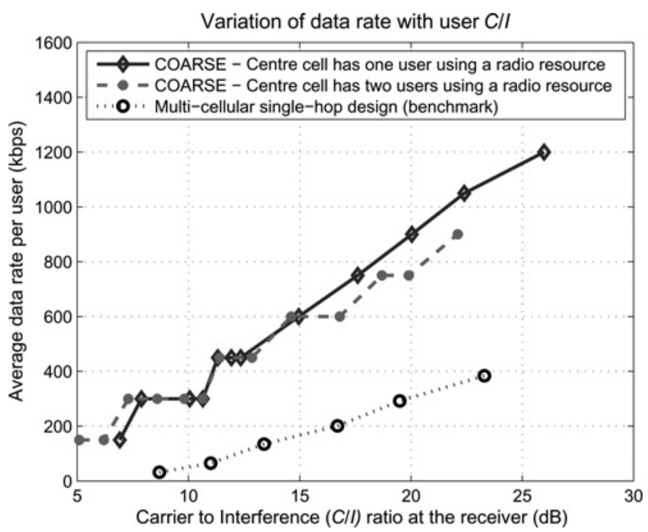

Fig. 5 *Variation of data rate per user with carrier-to-interference ratios*

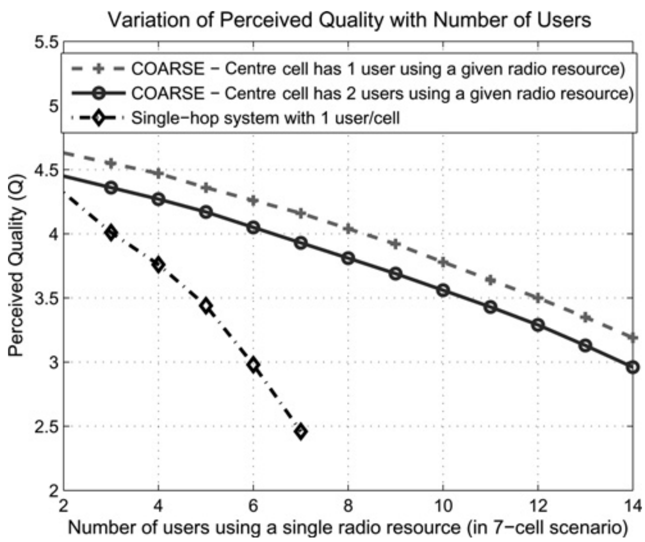

Fig. 7 *Variation of calculated video quality with varying number of users*

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(which amounts to 'fair' as per ITU-T R. P.910 standard). However, in case of an equivalent single-hop network, with seven users across seven cells, the average Q is <2.5 (close to 'bad'). This clearly shows the improvement in the video quality obtained by using a COARSE scheme, as compared with a single-hop cellular network.

It should be noted that the absolute values of data rate and perceived quality shown in Figs. 6 and 7 could be varied by changing the bandwidth or by considering more cells under a single MSC. However, the significance of the result is the overall improvement through COARSE and importantly, a stepwise change in the data rate and video quality, obtained through COARSE.

5 Conclusions

COARSE proposed in this paper is a cross-layer solution for achieving high-quality adaptive video transmission in a two-hop cellular network. The main advantage of COARSE is that the perceived quality of the video stream can be adapted dynamically in real time at the application layer, by varying the radio resource allocation at the link layer and the user data rate at the physical layer. COARSE offers two significant benefits that would be extremely vital for the next generation wireless systems. Firstly, the cluster-based scheme in COARSE enables a frequency reuse of one. Secondly, the variation of the video-perceived quality enabled by COARSE is obtained in a controlled manner, which is critical for multimedia streaming/next generation video-intensive wireless networks. A future work in this direction is to incorporate the network and transport layer design aspects into COARSE and formulate an integrated adaptive scheme that optimises the solution over several layers, including the network layer. The future research would investigate the amount of benefit that could be obtained from such an integrated adaptive scheme.

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