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N° 7442

October 2010

Rapport de recherche

ISSN 0249-6399 ISRN INRIA/RR--7442--FR+ENG

INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

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Anis Ouni*†, Hervé Rivano‡† , Fabrice Valois†

Thème : 1
Équipes-Projets SWING

Rapport de recherche n° 7442 — October 2010 — 14 pages

Abstract: We consider a multi-hop wireless mesh network composed by routers which route traffic to the Internet through several gateway. In such network, a bottleneck phenomenon limits the performances around the gateways, the network capacity does not scale with its size. In this work, we propose a traffic scheduling strategy around the gateways in a 802.11-based wireless mesh network. We distinguish two kinds of nodes according to their location in the network and the medium sharing strategy used: those located within k-hop of the gateway run a TDMA medium access protocol while the nodes further run a CSMA/CA MAC layer. We investigate on the impact of the size of the TDMA area on the network capacity when an optimal scheduling is implemented. Through extensive simulations, it is shown that network capacity, fairness and packet loss rate are improved by our approach.

Key-words: Wireless mesh network, network capacity, quality of service, traffic scheduling.

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Résumé : Nous considérons un réseau radio maillé multi-saut constitué de routeurs qui acheminent le trafic à Internet via plusieurs passerelles. Dans certain réseau, de nombreux travaux ont montré que la capacité était contrainte par la congestion autour des passerelles. Dans ce travail, nous proposons une stratégie d'ordonnancement de trafic autour de la passerelles dans un réseau maillé sans fil de type 802.11. Nous étudions l'impact sur la capacité d'un accès au médium TDMA dans le k-voisinage de la passerelle et CSMA/CA au-delà. Deux stratégies sont considérées : la première augmentant le nombre de slots dans la zone TDMA après avoir déterminé son ordonnancement optimal tandis que la seconde vise à augmenter la taille de la région TDMA. En se basant sur un large éventail de simulations, nous montrons que ces deux approches permettent d'accroitre les performances du réseau en terme de capacité et de taux de pertes.

Mots-clés : Réseaux Radio Maillés, capacité, qualité de service, ordonnancement de trafic.

Wireless mesh networks (WMNs) have emerged recently as a promising technology to support high data rate requirements and to ensure a quality of service to the users [1]. In this paper, we consider a wireless mesh network composed of a twofold architecture (fig. 1). On the one hand stationary or mobile clients are connected to access point through wireless links. On the other hand a wireless backhaul topology interconnects the access points with the Internet. These access points are equipped with a routing functionality and communicate together through radio links. Their role is to collect the traffic generated by the potentially mobile clients and forward it through multi-hop communications toward some dedicated routers, called gateways, that bridge the backhauling network to the Internet.

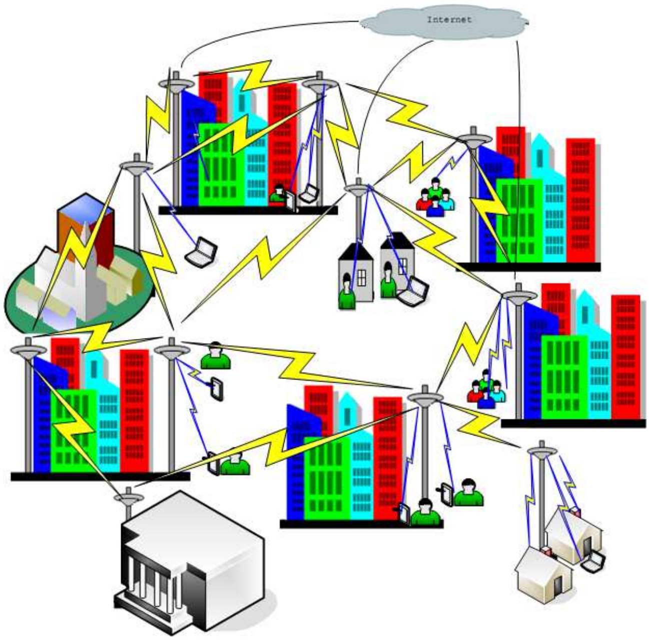


Figure 1: Wireless mesh network architecture: routers collect the traffic from clients (mobile or static) and forward it to the Internet through gateways.

Providing a better quality of service to a larger number of users is a key challenge for wireless mesh networks. Indeed, many papers of the literature have highlighted a critical behavior of the capacity [2, 3, 4]. They have pointed out a bottleneck around the gateway that limits the network performances, particularly the network capacity. A shared conclusion of these studies is the weakness of random access performed by CSMA/CA to provide and to guarantee bandwidth to users when the traffic becomes intense [4]. Optimal bandwidth allocations schemes have been presented assuming a fined-tuned TDMA MAC layer [2, 3]. The heart of these solutions is the computation of a call scheduling coping with the interferences: the goal is to allocate to each node a sequence of time slots to transmit, such that a maximum number of pairwise non-interfering transmissions are packed into each time slot. Unfortunately, computing such scheduling has a high complexity [5] and performing the TDMA at the whole network scale is very expensive in terms of signaling (synchronization, slots allocation, ...).

In order to cope with the drawbacks of both CSMA/CA and TDMA, mixed solutions have been proposed in the context of wireless sensor networks which suffer a similar issue: when the traffic intensity increases, collision, congestion and packet loss appear, mainly around the sink. In particular, one has proposed a new MAC protocol combining the idea of TDMA with a CSMA/CA into a slotted CSMA/CA scheme close to the sink, and a classical CSMA/CA further [6] .

In this paper, we take another viewpoint and do not propose any new protocol. Our approach consists in combining out-of-the-self 802.11 like CSMA/CA with a TDMA in order to achieve performances close to the theoretical optimal while maintaining a low computation and signaling complexity.

We focus on traffic scheduling in areas characterized by a huge traffic and where a bottleneck is present. We distinguish two kinds of nodes: those located within k-hop of the gateway run a TDMA medium access protocol, while the nodes further run a 802.11 like CSMA/CA MAC layer [7]. The TDMA is the optimum obtained by known methods [3] applied on the first kind of nodes plus extra time slots dedicated to gathering the traffic of the second kind.

We consider two complementary definitions of the capacity. A first one, denoted *network capacity*, is a measurement of the behavior of the whole network. It is defined as the sum of the traffics that have reached the gateways to the Internet. A second one, denoted *flow capacity*, measures the capacity of each flow, that is the quantity of bandwidth allocated to the traffic collected by each router.

We focus on the following issues:

- What is the size of the TDMA area which allows the best network performances?
- What is the relationship between the k-hop scheduling and performances?
- How much can we improve the network performances using a traffic scheduling?

Through extensive simulations, we show that network capacity, fairness and packet loss rate are improved using these approaches and that the size (k) of the TDMA area is kept low enough for a practical implementation.

This article is organized as follows. The next section discusses related work where we review the basic research that studied the radio network capacity. Section 2 is dedicated to describing the methodology of our work, the assumptions made, and the concept of network capacity with two different objectives. Then, Section 3 is devoted to the study of scenarios and analysis results. The last section concludes our work and presents the prospects and directions for the continuation of these researches.

1 Related work

Several articles have addressed the capacity of wireless network, with various definitions. In [5], the capacity represents the quantity of flow that can be allocated proportionally to the users demand. In [8,9,10], the capacity is defined as the maximum bandwidth that can be allocated to each user. The study of the capacity may have different objectives. For an operator, the objective is to increase the number of served users while ensuring a reasonable quality of service. For the user, improving the capacity is to obtain more bandwidth to increase his end-to-end flow.

Capacity evaluation in these networks has fostered an important research effort since one of the major issue of wireless networks is the capacity reduction due to radio interferences [11, 12]. Several works focused on dedicated radio network topologies [8, 13] underline the highly sensitive behavior of the radio capacity. They showed that the capacity of a node in an ad-hoc wireless network decreases with $\frac{1}{\sqrt{n}}$ when the network cardinality, n, increases.

Unlike ad-hoc networks, wireless mesh networks are static and have bottlenecks located around the gateways. Therefore, the available capacity allocated to each node is reduced by a factor of $\frac{1}{n}$ [9]. This result is extended in [14], which evaluates the difference of capacity provided by an ad-hoc network or an hybrid network, using linear programming models. In [4], the regularity of the topology, the placement of gateways and the routing protocols are shown to have a limited impact on the capacity, which is directly bounded by the bottleneck around the gateway [2, 3].

In order to cope with this, optimization approaches and heuristics have been investigated trying to maximize the network capacity. In [3,15], linear programming models of wireless mesh networks have been developed in order to compute a joint optimal resource allocation and routing. One of their main results is the identification of a critical area, located around the gateways, and characterized by an heavy congestion. Other studies have addressed the scheduling problem around an access point. A Round Weighting Problem (RWP) has been studied in [16] in order to determine the minimum number of rounds (a round is any set of pairwise disjoint edges). In [5], a study of the Round Weighting Problem (RWP) is addressed in the case of a grid topology where a bridge is located in the center or in the corner of the grid. The goal is to determine the optimal weight of a round depending on the amount of total traffic network.

Other researches have been carried out on medium access protocols for wireless sensor networks, many of them try to mitigate the drawbacks of CSMA/CA using other MAC layer protocols [17]. In particular, [6] proposes funneling-MAC, a hybrid MAC protocol which defines an area around the sink in which a slotted CSMA/CA is performed. Outside this area a classical CSMA/CA is ran.

In Funneling-MAC, the TDMA scheduling is managed by the sink using beacon packets. The periodic transmission of those packets consumes a lot of bandwidth [14]. However with a high traffic or a large number of sources, the packet loss rate in this protocol is higher than 40% in one-hop nodes even with the TDMA approach. Our approach offers null loss rate in one-hop nodes taking advantage of an optimal scheduling around the gateway (see Figure 7(b)). In our work, there is not an energy constraint as in sensor network, and thus we do not require a power control.

2 Background and methodology

We consider a synchronous wireless mesh network using a single radio channel shared among all routers. We study a grid topology composed of 121 nodes (11x11), where a gateway is located in the center to forward all network traffic to the Internet. The upload traffic in the network is uniformly distributed among the routers. Each router, periodically, sends a given quantity of traffic which represents the aggregate traffic of its clients. This traffic is routed to gateways through multi-hop paths. We assume that the communications in the infrastructure do not interfere with any other communication. We also assume that the interfaces connecting the gateways to the Internet have infinite capacity. Our study hence focuses on the behavior of the backhaul network.

Even though the scheme we introduce is generic and independent on the interference model, the simulation results we present are obtained with an euclidean distance based interference model: two nodes do not interfere *iff* there are at least $2 * d_t$ apart, where d_t is the euclidean transmission distance.

2.1 Approaches proposed

The main result of the related work part is to consider a communication architecture including both TDMA and CSMA to improve the capacity. So we propose to study the traffic scheduling around the gateway. We distinguish two types of area : the first one is the TDMA area around the gateway that contains the nodes located within k-hop of the gateway they use a TDMA medium access protocol. The remaining is the CSMA area, in which nodes use CSMA/CA (Fig 2). Furthermore, we propose two strategies to improve network performances: the first approach consists, in firstly, determining the optimal scheduling for the TDMA area and then, the number of slots allocated to this area is increased to gathering the traffic of the CSMA area. The second consists in tuning the size of the TDMA area to keep it as small as possible with good performances.

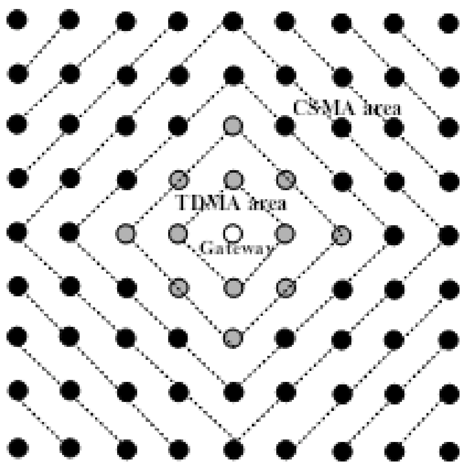


Figure 2: Communication architecture: TDMA nodes located in the k-hop of the gateway, other nodes use CSMA/CA.

2.2 Optimal scheduling

We consider a synchronous network and a time period divided into slots of equal duration. We compute an optimal scheduling based on the "Round Weighting Problem" [3], where each slot is assigned to a set of pairwise non interfering links (round). The objective is to minimize the sum of the rounds weighting. For this, we compute a scheduling communications that guarantees us to flow p(v) packets for each node, v, in the network for a minimum time (period T). By minimizing this period, the traffic of each node will be transported with a maximum flow p(v)/T. To respect the interference constraints, the links activated together must be pairwise non interfering. To do this, communications must be scheduled in time.The definition of rounds and the determination of optimal weights are derived from [3].

A example is depicted in Fig. 3 using a distance-2 geographic interference model. Here, every node send periodically one packet to the gateway. For instance, the links e1 and e4 can be active simultaneously without interference: they can thus be in the same round. Similarly, one can see that links e_2 and e_3 can't be active together. Finally, we have three rounds : $R_1 = \{e_1, e_4\}, R_2 = \{e_2\}$ and $R_3 = \{e_3\}$. To respect constraint of flow conservation and nodes demand, the minimal number of rounds activation to flow all the traffic is: $W(R_1) = 1, W(R_2) = 2, W(R_3) = 3$. So, the minimum period, to flow a packet for each node to the gateway, is 6 slots.

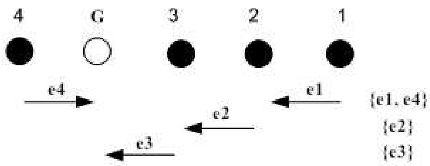


Figure 3: Example of scheduling with 4 nodes and a gateway.

2.3 Performance evaluation criteria

2.3.1 Network capacity

In our work, the network capacity is the quantity of traffic sent by all nodes ($\mathbb{N}$) and forwarded to the Internet through the gateway during the simulation period. This metric represents the maximum quantity of traffic that the network can transmit to the Internet, and calculated as follows.

$$C_{\text{network}} = \frac{\sum_{n \in \mathbb{N}} |\text{Received\_packets}(n \rightarrow \text{gateway})|}{\text{Simulation\_time}}$$

2.3.2 Flow capacity

It is defined by the sum of traffics sent by a given router and received by the gateway during the simulation period. This metric illustrates the bandwidth consumed by each router in the network. Thus, it allows to study the problem of unfairness in the distribution of bandwidth among the flows. This is a key point of the quality of service. In fact, an operator must ensure a bandwidth acceptable for each node in the network. This metric is calculated as follows.

$$C_{\text{flow(n)}} = \frac{|\text{Received\_packets}(n \rightarrow gateway)|}{\text{Simulation\_time}}$$

These two metrics are complementary because the first one gives a global vision of the network while the second one gives a detailed view.

2.3.3 Loss rates per node

It's desirable to measure the per node packet loss at each node in the network, in order to determine the area characterized by a important loss rate.

In this paper, the flow capacity and loss rate are presented by *level*. A *level* is the set of nodes that have the same distance in terms of number of hops from the gateway. All the following results are obtained through extensive simulations using the WSNet simulator [18] so as to guaranty a confidence interval of 95%.

3 Performance evaluation

First, we study the performances of a network using only CSMA/CA, then we focus our simulation on the two approaches proposed previously.

3.1 Simulation setup and parameters

Our studies and evaluations are based on simulations only. In the WSNet discrete event simulator [18], the TDMA protocol is implemented in such a way that a node can communicate with a TDMA node and also with a CSMA node. For sake of clarity, we do not consider the traffic of control messages that can we assume to be sent during extra time slots. This problem has been addressed by several works, where some slots are dedicated for the synchronization and scheduling [19, 20]. In addition, in our work, we show that the TDMA area can be kept small with respect to the size of the network, which reduces the complexity of the control issue.
The studied network is composed of 121 nodes in a 11 by 11 grid where a gateway connected to the Internet is positioned in the grid center. A physical layer taking into account the phenomenon of attenuation in free space and a geometrical model of interference limited to two hops is used to model the radio link. The routing used in the CSMA area is based on shortest path routing.

3.2 Study of CSMA/CA

Figure 4 shows the evolution of the average flow capacity by level: clearly the network bandwidth sharing is unfair. Only nodes close to the gateway use a large share of bandwidth, while very few packets of their successors reach the gateway. This result, confirmed by other works [21, 22], highlights the fairness problem that could occur using CSMA/CA. In fact, the packets issued by the furthest nodes have a low probability to reach the gateway, because the distance (hops number) between these nodes and the gateway is more important: it increases the collisions and interferences on the multi-hop path.

Figure 5 shows the variation of the average loss rate by level. In moving towards the grid center, the loss rate becomes more important. In fact, the nodes that are located at the center of the grid are characterized by a strong constraint caused by the congestion, interferences and collision around these nodes, while nodes in the grid border face a more limited interference.

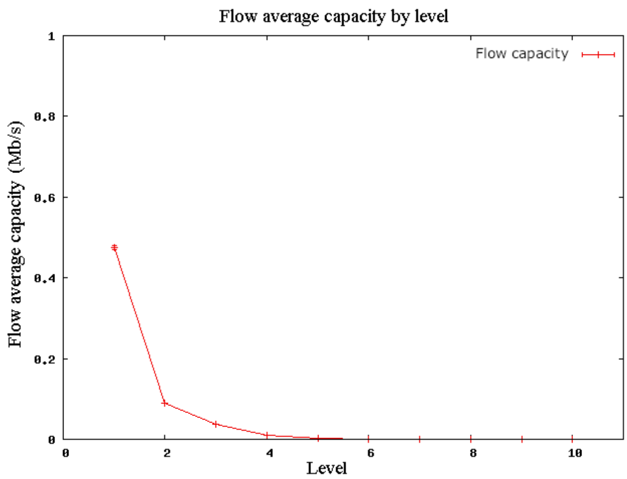


Figure 4: Flow average capacity by level (grid 11x11, CSMA/CA only).

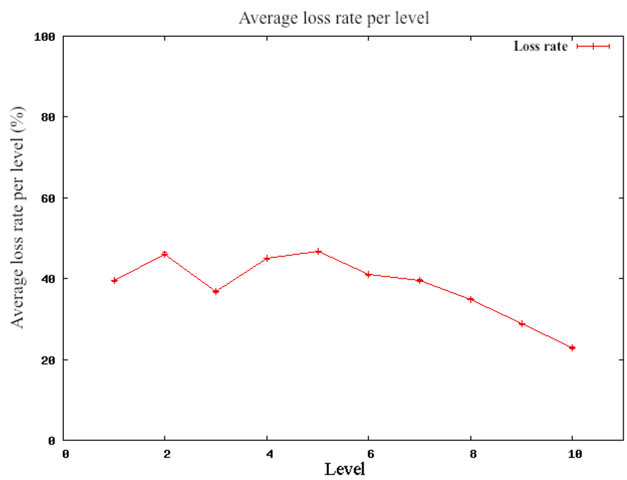


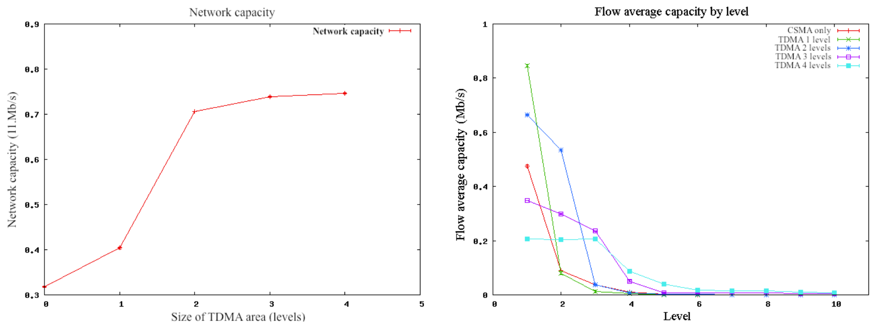
Figure 5: Average loss rate by level (grid 11x11, CSMA/CA only).

3.3 Impact of the size of the TDMA area

We study the impact of increasing the TDMA area on the network performances: from a TDMA area located only in the 1-hop neighborhood of the gateway to a TDMA area covering the nodes into the 4-hop neighborhood. We calculate, each time, the optimal scheduling that can flow the all traffic of TDMA nodes for a minimum period of time as described in [15].

The simulation results for the variation of network capacity according to the size of the TDMA area are given in figure 6(a). Increasing by one or two levels the TDMA area leads to a remarkable improvement of the network capacity, while it tends to be constant after the third level. In fact, to improve the capacity of the network, it is interesting to reduce the interferences on the nodes around the gateway which route all the traffics of the network. Thus, for a two hop interference model, it is necessary to optimize at least three levels around the gateway. It is noticeable that these results are confirming the theoretical results obtained by [3].

Figure 6(b) illustrates the average flow capacity by level with respect to the increase of the TDMA area. We notice that when the scheduling area increases, the number of nodes that take advantage of the bandwidth increases too. Moreover, the flow capacity tends to be fair between TDMA nodes.

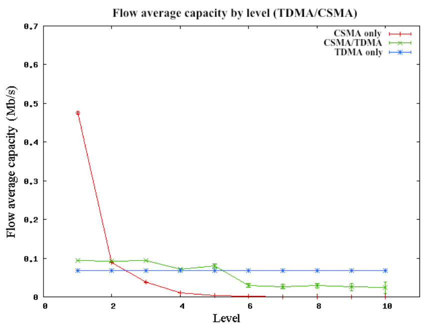


(a) (b)

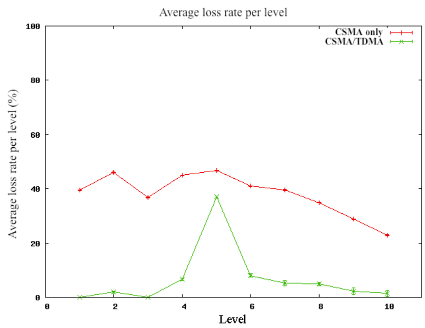
Figure 6: Network capacity (a) and average flow capacity by level (b) according to the increase of TDMA area.

3.4 Fairness and packet loss

In this scenario, the TDMA area is set at 4 levels and the number of slots is *computed* in order to provide an optimal use of bandwidth. Figure 7(a) (resp. Figure 7(b)) represents a comparison between the flow capacities (resp. the loss rate) in the case of a network without scheduling (CSMA/CA only) and network with a scheduling of four levels around the gateway. We show that the scheduling significantly improves network performance. The bandwidth is well shared by all nodes in the network, the flow capacity for each node tends to a fair average capacity presented by the horizontal line (case of a network working with TDMA only). The capacity of the network is increased more than of twice (fig 6(a)). Note that the loss rate is decreased strongly with the scheduling and that the loss is concentrated on the border TDMA/CSMA (level 5). This peak is due to the problem of synchronization between TDMA and CSMA nodes.



(a) Flow average capacity by level.



(b) Average loss rate by level.

Figure 7: Performance comparison between TDMA-CSMA (RG4-4) and CSMA (RG0).

3.5 Discussion

Note that the use of only TDMA in the network leads to good network performances (weak loss rate, fair bandwidth sharing, ...), but the problem is that TDMA appears to be expensive in terms of nodes synchronization and slots allocation. Also, the use of the bandwidth will not be effective if a node does not use its own slots. Moreover, in the case of disappearance or appearance of a node in the network, it is necessary to update the scheduling to make it optimal. For this, it is better to schedule the traffic in the area where bottlenecks appear, and to keep the rest of network operating in CSMA: this kind of solution should guarantee an acceptable quality of service (low loss rate, good bandwidth, ...).

Note that these results can be improved if we avoid the loss rate on the border of CSMA-TDMA. Currently, we are studying the behavior of communication between a TDMA and CSMA node. The goal is to have reliable communication with a large capacity and low packet loss.

4 Conclusion

In this work, we propose a traffic scheduling strategy for the bottleneck area (gateway) in a 802.11-based wireless mesh network. This traffic scheduling is based on a TDMA medium access in a small area around the gateways and CSMA/CA further. To increase the network performances, we presented two main strategies: firstly, determining the optimal scheduling for the TDMA area and then, the number of slots allocated to this area is increased to gathering the traffic of the CSMA area. The second consists in tuning the size of the TDMA area. We show that these approaches can significantly improve the network performances. Further work should be conducted to address the concentrated packet loss at the TDMA/CSMA border. Because only the grid topology is addressed, it would be also interesting also to extend this study to random topologies.

5 Acknowledgment

This work has been partially funded by ANR VERSO ECOSCells.

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ISSN 0249-6399