Cross-layer based erasure code to reduce the 802.11 performance anomaly

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Cross-Layer Based Erasure Code to Reduce the 802.11 Performance Anomaly: When FEC Meets ARF

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ABSTRACT

Wireless networks have been widely accepted and deployed in our world nowadays. Consumers are now accustomed to wireless connectivity in their daily life due to the pervasiveness of the 802.11b/g and wireless LAN standards. Specially, the emergence of the next evolution of Wi-Fi technology known as 802.11n is pushing a new revolution on personal wireless communication. However, in the context of WLAN, although multiple novel wireless access technologies have been proposed and developed to offer high bandwidth and guarantee quality of transmission, some deficiencies still remain due to the original design of WLAN-MAC layer. In particular, the performance anomaly of 802.11 is a serious issue which induces a potentially dramatic reduction of the global bandwidth when one or several mobile nodes downgrade their transmission rates following the signal degradation. In this paper, we study how the use of adaptive erasure code as a replacement of the Auto Rate Feedback mechanism can help to mitigate this performance anomaly issue. Preliminary study shows a global increase of the goodput delivered to mobile hosts attached to an access point.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless communications

Keywords

Cross-layer, erasure code, 802.11

General Terms

Algorithms, Design.

1. INTRODUCTION

The next generation 802.11n wireless network is being standardized by adding several powerful technologies like MIMO [10] and $40MHz$ operation [11] to the physical layer which allow to support much higher transmission rates and a wider signal coverage. However, one of the core features of 802.11, the contention based CSMA/CA access method, has never be changed since its first original version. This contention based channel access method guarantees equity for long term channel access. This access method entails a round robin scheduling for the access to the medium by the mobile hosts attached to the same access point. This long term behavior is at the origin of a syndrome called 802.11 anomaly caused by low rate senders lowering the performance of fast senders and inducing a strong correlation between the collective and the individual performances [7]. Indeed, in order to optimize the individual goodput (meaning the application level throughput), the Auto Rate Feedback (ARF) mechanism applied by the 802.11 MAC layer, dynamically adapts end-systems sending rate according to dynamic channel communication conditions.

In this paper, we will show that a systematic recourse to the ARF mechanism, when communication conditions worsen, is not always the best solution. We demonstrate that cross layer cooperation between an adaptive upper layer FEC based mechanism[1] and the ARF mechanism can alleviate this performance anomaly and improve the overall goodput. Indeed, instead of having systematically recourse to the ARF mechanism when communication condition worsen, our approach aims at keeping the current communication rate and increasing the reliability of the current communication context by, in first resort, applying to the packet flow a FEC mechanism of which the expansion ratio is defined according to monitored Packet Error Rate. This paper assesses the limit of this approach and makes explicit the threshold when ARF has to take over from FEC for ultimately delivering smoother and more efficient rate variations than the

[1] also known as erasure code

usual ARF mechanism alone. We show in our simulation and trace based measurements that our proposal can significantly increase the global goodput of the mobile nodes in certain communication contexts.

This paper is organized as follows, in section 2, we give a brief introduction of the 802.11 performance anomaly; in section 3, we present our FEC based mechanism and an analysis of the gain in terms of global goodput obtained by our proposal. We provide a preliminary validation in section 4. Finally, we conclude and discuss this proposal in section 5.

2. CONTEXT OF THIS WORK

Cross-layer reliability management is definitely an open problem in wireless networks (see *e.g.* [4] or [2]). Classical mechanisms are error correcting codes and modulation at the physical layer, erasure codes or retransmissions at the link and/or the transport layer. The choice between these possibilities must be carefully done by taking into account the properties of the channel and the interactions between the mechanisms (see *e.g.* [3]). From this viewpoint, a transmission using TCP/IP over 802.11b already uses a multi-layer reliability system, mixing retransmissions mechanisms at the transport and at the link layer and adaptive modulation at the physical layer. The components mechanisms and the parameters of this system were tuned in order to provide the best reliability to each connection. However, an unexpected consequence of this complex system is the "anomaly" phenomenon of 802.11 [7]. Clearly, the best way to solve this anomaly is to rethink the whole reliability system. Unfortunately, due to the wide deployment of this technology, it is more realistic to not strongly modify the mechanisms of the lower layers but rather to propose new solutions for the higher layers. This is the main objective of this work.

In [7], Heusse et Al. provides a performance analysis of the IEEE 802.11b networks. Through simulation and experimental work, they show that overall performances are considerably degraded when mobile hosts transmit with a lower rate than others in the same hot-spot. The contention based CSMA/CA access method is demonstrated to be the root cause of this problem known as the 802.11 performance anomaly.

This anomaly phenomenon is illustrated Figure 1. In this figure, we report the UDP throughput of each mobile node in AP's coverage in terms of number of the uploading mobile nodes ($N = [4, 30]$) in four different scenarios. In the first scenario, all the mobile nodes have a transmission rate of 11Mb/s. Then, for each other three scenarios, one among N mobile nodes has respectively a transmission rate equal to $5.5Mb/s$, $2Mb/s$ and $1Mb/s$. This figure shows the degradation performance when one mobile node among N emits with a lower transmission rate.

In [12], the authors propose a deeper analytical study of this anomaly performance and obtain similar results. Several contributions attempted to solve this anomaly issue [6, 5, 9]; however, all of them require modifications on the MAC layer, which makes difficult their wide deployment. The origin of physical layer rate variations suffered by mobile node takes its root in the Auto Rate Feedback mechanism that aims to discretely adapt mobile nodes communication rate according to the monitored channel state. The loss rate is the parameter usually monitored by wireless cards for channel state estimation purpose. Consecutive packet losses, after applying some degree of ARQ persistence, are then con-

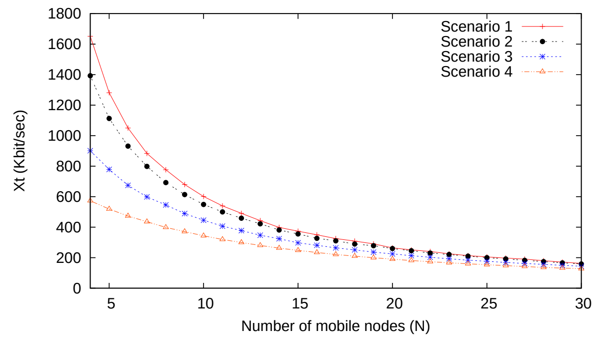


Figure 1: Evolution of UDP throughput as a function of the number of uploading mobile nodes

sidered for downgrading the current selected rate in order to improve the quality of the transmission. Conversely, consecutive successful packet transmissions lead end systems to upgrade their transmission rate. Performance anomaly aside, such communication rate enslavement to the channel conditions potentially induces erratic rate changes that have a negative impact on the quality of transmission [13].

Few contributions have tackled the performance anomaly issue with a non intrusive approach for the CSMA/CA access method. In the following of this paper, we introduce an original cooperative scheme between the ARF mechanism at the origin of discrete communication rate variation and an upper layer Forward Error Correction mechanism. Instead of applying significant discrete rate changes when an error threshold is overcome, we give the flour first to an adaptive FEC mechanism that aims to reduce the losses observed at the current rate and coding conditions. The usual ARF mechanism takes over when the safe state of this "FEC extended channel" cannot be preserved anymore. This cooperative scheme between FEC and ARF aims to induce a more continuous rate delivery to application flows and to reduce the 802.11 performance anomaly by preserving simultaneously individual and collective interests of mobile nodes. Furthermore, the approach promoted in this paper entails no change in the 802.11 MAC layer if the option to enable and disable the ARQ mechanism is available.

In a previous work, we have proposed an analytical model [13] to efficiently estimate the maximum bandwidth supported by MAC layer in the context of 802.11 wireless networks. We showed that this maximum bandwidth can be accurately processed according to: the number of mobile nodes; the flows' profile and the physical layer transmission rates. This analytical model is used in this paper to estimate the global goodput gain brought by our proposal.

3. CROSS-LAYER-BASED ERASURE CODE

This section describes our proposal to alleviate the performance anomaly of 802.11 and to offer a significant gain on the aggregated goodput delivered to the mobile nodes attached to the same access point (we denote this global gain: GG) compared to the traditional scheme defined in 802.11 standard. The purpose of our contribution aims to increase the collective aggregated mobile nodes goodput while not sacrificing individual goodput. Therefore in order to estimate the individual impact of our approach we also define the individual gain (GI) of the FEC-based mobile nodes as the ratio between the goodput delivered by our approach and the one delivered by the standard.

3.1 The 802.11 standard

For generality purpose, we suppose that N mobile nodes are associated to an 802.11b access point. All of them are supposed to have initially a stable transmission rate of Tr_i with $Tr_i = (11, 5.5, 2, 1)Mb/s$ for $i = (4, 3, 2, 1)$. We also suppose that N_2 mobile nodes (among the N mobile nodes) are moving away from the AP. Following the 802.11 standard, their transmission rates will be downgraded to Tr_{i-1} after time t and according to [1], exactly after 2 consecutive packets lost over the wireless channel. The analytical model previously introduced in [13] gives the maximum uploading bandwidth (R) offered by the MAC layer to each of the N mobile nodes. We denote p, the Packet Error Rate that for clarity purpose (without sacrificing the generality of our approach) is supposed equal for all the mobile nodes that have downgraded their rate. The aggregated useful uploading throughput of the N mobile nodes is given by:

$$N * R * (1 - p) \tag{1}$$

and the individual goodput is:

$$R * (1 - p) \tag{2}$$

Usually, small values of p are observed as the adaptive modulation is efficient enough to assure a low PER. These calculated uploading goodputs will be compared to those resulting from our proposal.

3.2 Our proposal

In this section, we present our FEC based method and an analysis on the gain brought by our proposal in terms of number of mobile nodes and the applied redundancy ratio.

3.2.1 Algorithm

As illustrated in Figure 2, our proposal is initially triggered when M consecutive packets are lost in the wireless link (*i.e.* M=2 according to the 802.11 standard). Following such a loss event, the transmission rate is downgraded according to the usual ARF mechanism. Instead of downgrading the rate, we propose to maintain the current transmission rate (Tr_i) and adaptively enforce reliability with redundancy packets added by the IP layer. The proportion of redundancy packets among the whole set of transmitted packets is called redundancy ratio and is denoted rr. The redundancy ratio rr ($0 \leqslant rr < 1$) is estimated periodically every N_{pkt} packets sent by the wireless card (in our experiments, we set N_{pkt} to 50). During this N_{pkt} packets period, the MAC layer can monitor the number of packets successfully received by the AP according to the number of acknowledgments returned (N_{ACK}). The redundancy ratio able to correct this monitored loss rate is given by:

$$rr' = \frac{N_{pkt} - N_{ACK}}{N_{pkt}} \tag{3}$$

However, this processed redundancy ratio is based on a past state of the communication channel which may differ from the current one. Indeed, if we suppose that rr' is processed at instant t and directly used to build the redundancy packets, these packets will be sent out at $(t + \Delta t)$ due to buffering and processing delays at IP and MAC layers. As the channel conditions might have changed during this time interval, rr' might be no longer valid and might not be able to recover enough data at the receiver side. In order to address this issue, we introduce an estimation function Φ that takes into account the evolution of the redundancy ratio. The rr value is estimated to predict the variation of channel condition during the interval Δt. In the experimental part of this study (section 4), we used a proportional estimator derived from an offline analysis of the real wireless traces used in our experiments. The evaluation of others estimator is planned in a future work.

During a transmission, losses can occur following a burst pattern. If the burst pattern corresponds to N_{max} consecutive losses (in our experiment N_{max} is set to 5), we can asset that signal condition gets weak, then the transmission rate will be immediately downgraded from Tr_i to Tr_{i-1}.

We denote rr_{max} the maximum redundancy ratio. If the periodically estimated rr is bigger than rr_{max}, which means the useful throughput for the nodes implemented with FEC redundancy method is too little and is out of the tolerant range, then the transmission rate is immediately downgraded from Tr_i to Tr_{i-1}. Similarly to the 802.11 standard, the transmission rate increases from Tr_{i-1} to Tr_i when X (X can be set to 10 according to standards) consecutive packets is succeeded to be sent to AP by a mobile node. In our proposal, rr is reset and N_{ACK} is re-started to count every time when the transmission rate is changed. Figure 2 represents the basis of our algorithm.

In summary, when the channel conditions deteriorate, the mobile node, instead of downgrading its transmission rate at once, enforces dynamically the channel state with FEC in order to delay the occurrence of the performance anomaly syndrome. Such a conceptual approach raises the fundamental issues of the existence and determination of the threshold rr_{max} allowing the algorithm to switch from the "FEC extended" communication state to the ARF mechanism. Ideally the maximum admissible value, rr_{max}, that can be used for the redundancy ratio, should prevent the occurrence of the performance anomaly syndrome while preserving the goodput of the mobile nodes that enter in the FEC-extended communication state. Indeed, the proposed algorithm must prevent from replacing one anomaly by another which would lead to sacrifice significantly the individual goodput to favor the collective benefit. In the next section, we show such a maximum value exist and can be processed. Therefore the adaptive FEC processed in the framework of the proposed algorithm can be applied up to rr_{max} in order to increase the collective goodput while not sacrificing significantly individual benefit.

3.2.2 Critical redundancy ratio to have a gain

With our proposal, even when the N_2 mobile nodes' signal gets poor, we maintain their high transmission rate (Tr_i). According to [13], we can calculate the maximum uploading bandwidth (R_{FEC}) supported by the MAC layer for each of the mobile nodes. In the other hand, the estimated rr cannot guarantee to recover all the useful packets. We denote p' the percentage of the packets which cannot be recovered. We denote p, the PER of channel losses for mobile nodes with good signal (*i.e.* nodes not implemented with FEC mechanism), then, the aggregated uploading goodput of all

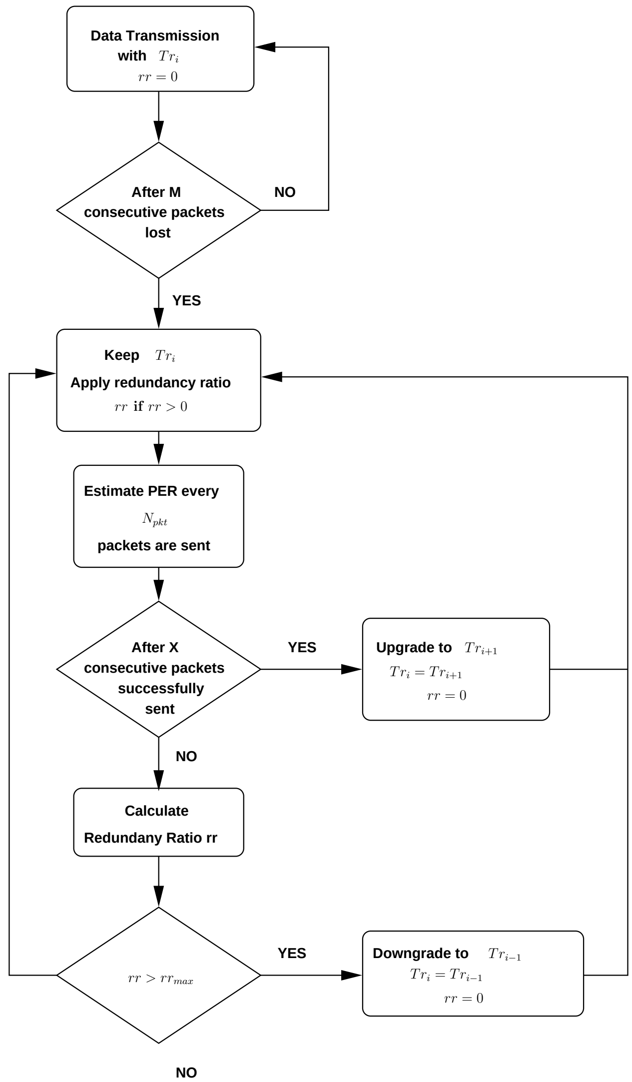


Figure 2: Algorithm

the N mobile nodes is:

$$N_1 * R_{FEC} * (1 - p) + N_2 * R_{FEC} * (1 - rr) * (1 - p') \quad (4)$$

and the uploading goodput for each N_2 mobile node is:

$$R_{FEC} * (1 - rr) * (1 - p') \quad (5)$$

Normally, the adaptive modulation is efficient enough to ensure a low PER (p). Compared to the PER for the FEC implemented mobile nodes, p and p' can be considered as negligible. In order to obtain a higher global goodput with our proposal compared to the standard, we should have:

$$N_1 * R_{FEC} + N_2 * R_{FEC} * (1 - rr) > N * R \quad (6)$$

when p and p' are negligible. Which means:

$$rr < \frac{N * (R_{FEC} - R)}{(N_2 * R_{FEC})} \quad (7)$$

We denote rr_{GG}, the redundancy ratio threshold allowing a global gain as follows:

$$rr_{GG} = \frac{N * (R_{FEC} - R)}{(N_2 * R_{FEC})} \quad (8)$$

In order to obtain a higher individual goodput for each N_2 mobile node with our proposal compared to the standard, we should have:

$$R_{FEC} * (1 - rr) > R \quad (9)$$

Which means:

$$rr < 1 - \frac{R}{R_{FEC}} \quad (10)$$

Therefore, the redundancy ratio threshold denoted rr_{GI} that delivers an individual gain is given by:

$$rr_{GI} = 1 - \frac{R}{R_{FEC}} \quad (11)$$

THEOREM 1. *Whatever the number of mobile nodes N, there is a redundancy ratio rr that satisfies simultaneously both global and individual gains (respectively denoted GG and GI)*

PROOF. Let's demonstrate that the individual redundancy ratio is always lower than the global redundancy ratio, that is: $rr_{GI} \leqslant rr_{GG}$ (*i.e.* (8) $\leqslant$ (11)).

Indeed:

$$\frac{R_{FEC} - R}{R_{FEC}} \leqslant \frac{N(R_{FEC} - R)}{N_2 * R_{FEC}} \iff N_2 \leqslant N$$

since $N_2 \leqslant N$ is always true, all the values in $(0, rr_{GI}]$ satisfy both individual and global gains. QED

The resulting rr_{GG} and rr_{GI} are represented as a function of N_1, N_2 and Tr_i in Figure 3 in the case where $Tr_i = 11Mb/s$ with FEC.

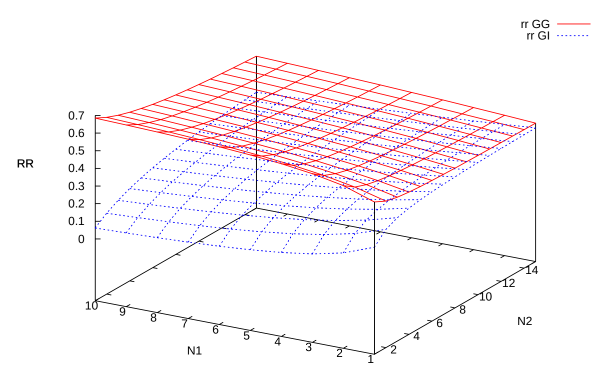


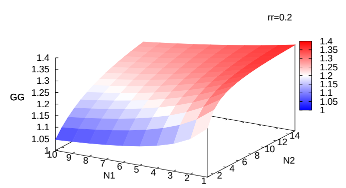
Figure 3: rr_{GG} and rr_{GI} thresholds as a function of N_1 and N_2

The above figure shows the existence of two distinct regions. The first one, associated to a redundancy ratio rr, lower than rr_{GG} but higher than rr_{GI} which delivers a global gain while sacrificing goodput for each of the N_2 mobile nodes that have recourse FEC (*i.e.* $GG > 1$ and $GI < 1$). The second region is defined by the values of estimated rr

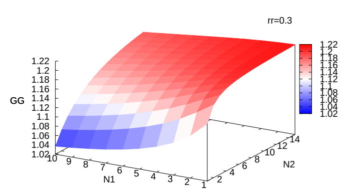
below rr_{GI} where we have both global and individual gains ($GG > 1$ and $GI > 1$).

The previous theorem shows that the redundancy ratio, that can be applied to a stream transmission in order to avoid a brutal rate decrease, covers an interval that can potentially lead to diverse policies going from the stringent respect of both individual and global goodput to the respect of global goodput only. This can result for instance in priority based policies that, according to the priority given to a node, can endeavor to more or less preserve the individual goodput of the considered node.

Moreover, we can observe in Figure 4 that a high redundancy ratio also impact negatively on the global gain. The policy function that applies an optimal trade-off between the global and individual goodput is highly dependent of the flow's types and will be carefully studied in our future work.



(a)



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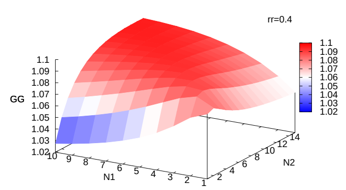

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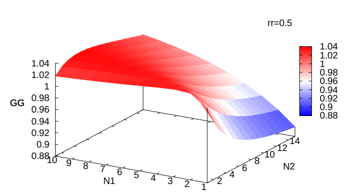

(d)

Figure 4: Global gain with a given rr as a function of N_1 and N_2

3.3 Proof of concept

In order to roughly assess the compatibility of the analytical model with real wireless signal behavior, we have experimentally measured the PER as a function of SNR for different transmission rates in the context of 802.11b (Figure 5). These measurements show that there is a clear covering of the curves of contiguous rates for a significant interval of SNR values. These results fit with the ones given in [8]

Therefore, these covering intervals give room for applying, at a constant given rate and up to a maximum redundancy ratio, the proposed adaptive FEC enhanced communication scheme which enhances flows goodput compared to a brutal rate downgrade.

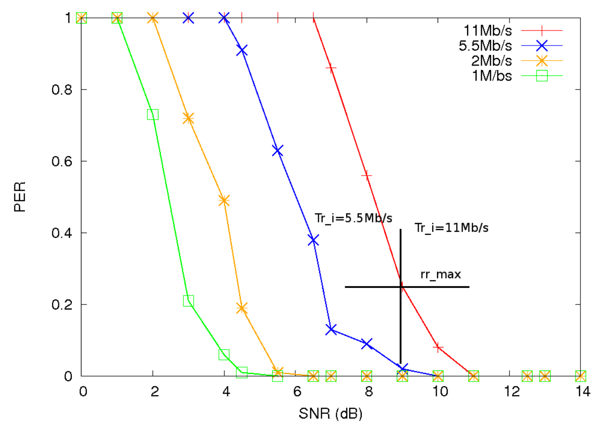

Figure 5: PER as a function of SNR

As illustrated in this figure, when the signal (SNR) degrades, the FEC implemented mobile node can maintain the current transmission rate ($Tr = 11Mb/s$ in the illustrated example) until the estimated redundancy ratio reaches rr_{max} which is defined as the critical threshold (represented here by the PER value of around 0.25). The transmission rate is downgraded after this maximum threshold

4. VALIDATION

We used real wireless traces to validate our proposal. The traces consist in a `tcpdump` output of UDP data and redundancy packets lost during a communication between 4 mobile hosts and one AP. During the experiment, three mobile nodes have a good signal coverage and a transmission rate $Tr_i = 11Mb/s$ ($N_1 = 3$). The fourth mobile node is initially in a poor signal coverage and then moves towards the good signal coverage zone for a while and returns to its initial point ($N_2 = 1$). During its move, the mobile node's transmission rate remains at $11Mb/s$ when the estimated rr is less than rr_{max} (we set $rr_{max} = 0.35$ in our experimentation). If the signal continues to degrade and the estimated rr is out of tolerated range ($rr > rr_{max}$), then the transmission rate of the moving node has to be degraded to $5.5Mb/s$.

In figure 6, curve1 (C1) and C2 represent respectively the goodput of the moving node and the global goodput of the 4 mobile nodes with the 802.11 standard (in this case, the transmission is directly degraded to $5.5Mb/s$ when signal is poor).

We can see in this figure that our proposal maintains a high transmission rate of $11Mb/s$ by applying FEC redun-

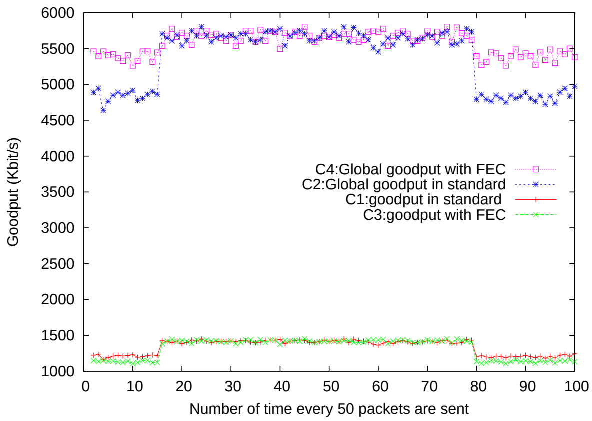

Figure 6: Validation result

dancy packets at the IP layer. The redundancy ratio rr is estimated periodically and applied to the IP layer packet when rr is lower than $rr_{max} = 0.35$. In this experimental test, we simply used a proportional estimator for the function Φ previously introduced. Indeed, this function is defined as follows: $rr = k * rr'$ where k results from an offline analysis of the loss evolution processed on our traces. We set k to 1.45 during our experiment to guarantee that 97.2% of useful data packets can be successfully received at the receiver side. According to this approach, the estimated rr ranges from 0.2 to 0.31. In figure 6, C3 and C4 represent respectively the individual goodput of the moving node and the global goodput of the 4 nodes when our FEC adaptive approach is used. Compared to the standard, although the goodput of the fourth FEC based mobile node slightly decreases ($GI = 0.93$), we can observe a significant global gain of $GG = 1.12$.

5. CONCLUSION

In this paper, we have shown a cross layer based cooperation between the 802.11 MAC layer and the adaptive FEC mechanism at upper layers, which is used to reduce 802.11 performance anomaly. Indeed, instead of downgrading the transmission rate when signal gets poor, we propose the mobile node to keep its current transmission rate and enforce its flows reliability with FEC redundancy packets. We have shown that our proposal can significantly reduce the 802.11 anomaly in several network conditions and increase nodes' goodput compared to the standard ARF approach. Our future work will be focus on the definition of efficient algorithms to predict the redundancy ratio and the definition of several joint rate-FEC adaptation policies that take into consideration the QoS constraints and the optimality criteria.

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