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Feedback Suppression in Multicast Satellite Networks Using Game Theory

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***Abstract*—Feedback implosion is a major problem limiting scalability in multicast satellite networks that arises when a large number of users transmit their feedback messages (FBMs) through the uplink channel, occupying a significant portion of system resources. This paper investigates how suppression of FBMs may be achieved through a novel feedback suppression scheme in which each user unilaterally decides whether to send a FBM or not. The users decisions are modeled applying game theory with inaccurate information. For this problem, the Bayesian equilibrium for the two and *N*-player game is investigated. It is proved that the feedback suppression game has a unique Bayesian equilibrium point. Then, based on appropriate numerical and simulation results, it is demonstrated that the proposed scheme avoids feedback implosion while at the same time it keeps feedback latency at very low levels. Finally, it is shown that the proposed scheme exhibits a significant performance improvement compared to existing exponential timer-based schemes.**

***Index Terms*—Bayesian equilibrium, feedback suppression, game theory, IP multicast, multicast satellite systems, reliable multicast, satellite networks.**

I. Introduction

Multicast is used to disseminate data to multiple receivers through a single transmission. Geostationary orbit satellites offer the advantage of multicasting data over large geographical areas without having to traverse several congested router hops with high packet delays. In providing large-scale reliable multicast services, a severe problem is feedback implosion arising whenever a large number of satellite terminals (STs) transmit feedback messages (FBMs) to the satellite. The number of these messages increase linearly with the number of STs and may lead to congestion.

Feedback implosion is a well-studied problem, especially for terrestrial networks [1]–[5]. In general, the proposed solutions are classified as structure-based or timer-based [6]. Structure-based approaches [7]–[11] rely on a designated site to process and filter feedback information. The members of a multicast group are organized in clusters that filter the amount of feedback generated by the group. On the other hand, timer-based solutions [12]–[18] rely on probabilistic schemes to suppress feedback at the source. The receivers delay their retransmission requests for a random interval that is either uniformly, exponentially, or beta distributed between the current time and the one-way trip time to the source. The goal is that group members closer to the source send their feedback sooner, suppressing feedback from members located further. Based on the resulting round-trip time (RTT), the sites use periodic session messages to measure their distance from the other group members.

Anyway, the existing solutions are not suitable for satellite networks due to several inherent characteristics, such as the high RTT, the fading due to atmospheric precipitation, and the diverse topologies of the deployed networks. Some fundamental issues concerning satellite multicasting are summarized in [19] and [20]. In the majority of the existing papers, it is assumed that the terminals communicate via terrestrial links. However, since this reduces the advantages from the deployment of satellite networks, in this paper, the problem of feedback implosion is dealt with under no such an assumption.

One of the first attempts to deal with the feedback implosion problem when the terminals do not have any terrestrial interconnection was presented in [21]. However, its main disadvantage is that the feedback suppression algorithm assumes deterministic timeouts requiring multiple RTTs over the high-delay satellite channel. Furthermore, in [22], a propagation-based feedback suppression scheme is proposed for rain-faded satellite networks. The algorithm immediately identifies the worst-performing user in the serviced area and designates him as the area representative (AR) based on the fact that the AR transmits FBMs faster than the other users, thus suppressing their feedback. In [23], a cluster-based algorithm is proposed where all Earth terminals belonging to the same cluster use a distinct return channel. The return channel may be reused by other clusters due to the low probability of the event that distant receivers send FBMs simultaneously. Another algorithm for feedback suppression [24] allocates return channels to receivers trying to minimize the total number of return channels used for feedback transmission. Finally, in [25], a feedback suppression algorithm is presented that reduces the number of uplink timeslots reserved for feedback transmission.

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It is evident that the feedback implosion problem can be dealt with if, on behalf of all multicast receivers, only a limited number of users send FBMs. The question that comes up is how to model the feedback suppression so that as the number of STs increases, their incentive to send an FBM is reduced. The answer to this question may be found to the game theory.

When a limited number of users receives multicast services, there is no need to suppress their FBMs. The impact on network performance is negligible, since a few FBMs do not require significant resources. On the contrary, when the number of users is high, the number of FBMs should be restricted below a threshold. Since, a single FBM may be sufficient to help all multicast users to recover from their packet losses, indifferent users who do not send FBMs contribute more to network performance improvement compared to users who send FBMs immediately.

In this paper, a game-theory-based feedback suppression (GTFS) scheme is presented. In this feedback suppression game, every player unilaterally decides whether to participate or not in the game by sending an FBM. If no player sends a FBM, a backup mechanism is activated to ensure that the game does not stop. Hence, if after a certain interval a player does not send an FBM, the backup mechanism enforces him to send an FBM. However, if at least one player sends an FBM, the lost packets of all players are recovered. In this case, users who did not send an FBM gain the maximum payoff, while users who sent an FBM have a certain cost.

The remainder of this paper is organized as follows. In Section II, the two-player feedback suppression game with inaccurate information is formulated. In this game, the benefits of contributing to the game are known to both players, but a player's cost is known only to him. For this game, the Bayesian equilibrium [26] is investigated. Then, the N-player version of the above game is analyzed. In Section III, the importance of introducing backup mechanisms to the GTFS scheme is demonstrated. Furthermore, the proposed schemes are compared to the existing timer-based feedback suppression scheme [12]. In Section IV, the performance of the proposed scheme in a high packet-loss rate environment is investigated. Finally, conclusions are drawn in Section V.

II. Feedback Suppression Based on Game Theory

A. Topology Description and Relevant Assumptions

A star-based network of $\aleph$ STs is considered. The STs do not have any direct interconnection and use the uplink channel to send FBMs to the satellite. Furthermore, the multicast information is separated into blocks of k packets and encoded using appropriate coding [27]. The key idea behind the employed coding is that at the sending end k packets of information data are encoded to produce n packets of encoded data, so that any subset of k encoded packets suffices to reconstruct the information data. Such an (n, k) code allows the receivers to recover from up to $n - k$ losses having occurred during the transmission of n encoded packets. In this analysis, it is assumed that when a ST looses more than $n - k$ packets, it sends an FBM asking for retransmission.

The above-mentioned coding scheme can reconstruct the transmitted information when the packet loss ratio is low. However, in modern satellite networks operating at the Ka frequency band (20/30 GHz) and above, propagation conditions, especially rain attenuation, severely impair link performance [30]. In this case, coding is not sufficient to guarantee reliable data transmission. Besides, due to rain attenuation, the satellite channel exhibits both spatial and temporal variations. Therefore, it is expected that a large number of STs simultaneously suffer from rain-induced attenuation [30]. Under these conditions, the probability that a large number of STs send, an FBM is high, resulting in feedback implosion.

B. Two-Player Feedback Suppression Game With Inaccurate Information

The feedback suppression problem may be modeled using game theory. The game belongs to the general class of contribution games [26], where each player has the choice to act contributing to the public good, but he would prefer that another player acts. In the feedback suppression game under consideration, any player who has lost a block of packets would like to send an FBM asking for retransmission, because recovering from the lost or corrupted block helps him to satisfy the quality-of-service (QoS) constraints for data transmission. However, no player wants to send an FBM because this action costs, either in consuming energy or in occupying resources. Since energy issues are of utmost importance with regard to satellite networks survivability, especially in mobile satellite systems [31], in this paper, the cost of sending an FBM is related to the energy consumption due to FBM transmission. Also, the possibility that no player sends an FBM should be prevented since, then, the QoS of all players would severely deteriorate. Therefore, an appropriate backup mechanism must enforce the dispatch of FBMs after a certain time period. Inevitably, this backup mechanism introduces delay. Hence, each player has two options, either send an FBM instantly, or delay its transmission.

Table I presents the feedback suppression game between two players who have lost the same block. If a player does not send an FBM instantly, he has a normalized payoff equal to 1 and no delay, provided that the other player sends an FBM. If both players risk and delay the transmission of the FBM, they both have a normalized payoff $1 - (\varepsilon_i + D_i)$, where

$$\varepsilon_i = w_e \cdot (dE/\alpha_i) \tag{1a}$$

$$D_i = w_D \cdot \mathrm{RTT}_i \tag{1b}$$

are the respective normalized energy and delay costs. In (1a) and (1b), dE is the energy consumption when an FBM is transmitted, α_i is the residual battery power of player i, $i = 1, 2$, at the time of decision, RTT_i is the respective RTT, and w_e, w_D are weighting factors related to the respective costs of sending an FBM instantly or not taking into account the energy constraints and the time sensitivity of the multicast service.

On the other hand, due to the energy cost of sending an FBM, if a player sends an FBM instantly, his payoff is equal to $1 - \varepsilon_i$. The rationale behind the selection of the normalized costs given in (1a) and (1b) is that when a user (player)

TABLE I
TWO-PLAYER FEEDBACK SUPPRESSION GAME

		Player 2	
		Delay FBM (p_2)	Send FBM ($1-p_2$)
Player 1	Delay FBM (p_1)	$(1-D_1-\varepsilon_1,\ 1-D_2-\varepsilon_2)$	$(1,\ 1-\varepsilon_2)$
	Send FBM ($1-p_1$)	$(1-\varepsilon_1,\ 1)$	$(1-\varepsilon_1,\ 1-\varepsilon_2)$

has abundant energy, he has no incentive to risk his QoS by delaying the transmission of his FBM. On the other hand, if his residual energy is limited, he takes the risk not to send an FBM and wait wishing that another user (player) would take the rap—in order to prolong his lifetime in the multicast service (game). In any case, it must be assured that the QoS of the multicast service (game) does not deteriorate. Therefore, after a certain time period, a backup mechanism must ensure that at least one of the users (players) will send an FBM.

The battery power of a user satisfies

$$\alpha_{\min} < \alpha_i < \alpha_{\max} \tag{2}$$

where $\alpha_{\min}$ is the threshold power rendering a user out of operation and $\alpha_{\max}$ is the maximum battery power. Assuming that $\alpha_{\min}$ and $\alpha_{\max}$ are common to both users

$$\varepsilon_{\min} < \varepsilon_i < \varepsilon_{\max} < 1, \qquad i = 1, 2 \tag{3}$$

where $\varepsilon_{\min} = w_e \cdot (dE/\alpha_{\max})$ and $\varepsilon_{\max} = w_e \cdot (dE/\alpha_{\min})$ denote the minimum and maximum normalized energy costs, respectively. It should be noted that it is common knowledge to the players that $\alpha_i,\ i = 1, 2$ are random variables following the same distribution over $(\alpha_{\min}, \alpha_{\max})$ with known strictly increasing cumulative distribution function $P\{\cdot\}$, that is

$$P\{\alpha_{\min}\} = 0 \qquad\qquad P\{\alpha_{\max}\} = 1. \tag{4}$$

Also, from (1b), it is observed that for each user i the cost D_i depends on RTT_i. It is clear that users with smaller elevation angles have higher delays. In this analysis, it is assumed that the users are distributed over the served area so that their elevation angles range from $\phi_{\min}$ to $\phi_{\max}$, corresponding to delays in the range $(D_{\min}, D_{\max})$, where $D_{\min} = w_D \cdot \mathrm{RTT}_{\min}$ and $D_{\max} = w_D \cdot \mathrm{RTT}_{\max}$.

A pure strategy for this game is a two-valued function $s_i(\varepsilon_i, D_i),\quad i = 1, 2$, mapping $(\varepsilon_{\min}, \varepsilon_{\max})$ into $\{0, 1\}$, where 1 signifies "send an FBM instantly" and 0 signifies "wait and send FBM." The payoff for two players are given from

$$u_i\left(s_i, s_j, \varepsilon_i, D_i\right) = 1 - \varepsilon_i s_i - (1 - s_i)(1 - s_j)(\varepsilon_i + D_i), \quad i, j = 1, 2,\ i \neq j. \tag{5}$$

A Bayesian equilibrium is a pair of strategies $\left(s_i^*(\cdot), s_j^*(\cdot)\right)$ such that for each player i and every possible pair (ε_i, D_i), the strategy $s_i^*(\varepsilon_i, D_i)$ maximizes the expected payoff $u_i(s_i, s_j^*(\varepsilon_j, D_j), \varepsilon_i, D_i)$ of player i over ε_j and D_j. Let

$$p_j = Pr\left(s_j^*\left(\varepsilon_j, D_j\right) = 0\right) \tag{6}$$

be the equilibrium probability that player j delays the transmission of his FBM. Then, the payoff of player i in case he decides to send an FBM instantly is given by

$$\pi_{\text{player } i \text{ sends FBM instantly}} = 1 - \varepsilon_i \tag{7}$$

while in case he decides to send an FBM with delay is

$$\pi_{\text{player } i \text{ sends FBM with delay}} = [1 - (\varepsilon_i + D_i)] \cdot p_j + 1 \cdot \left(1 - p_j\right). \tag{8}$$

Player i will send an FBM instantly if

$$\pi_{\text{player } i \text{ sends FBM instantly}} > \pi_{\text{player } i \text{ sends FBM with delay}} \tag{9}$$

or

$$\varepsilon_i/(\varepsilon_i + D_i) < p_j \qquad\qquad i, j = 1, 2,\ i \neq j. \tag{10}$$

Therefore, for $i, j = 1, 2\ \ i \neq j$

$$s_i^*(\varepsilon_i, D_i) = 1, \qquad \text{if } \varepsilon_i/(\varepsilon_i + D_i) < p_j$$

and

$$s_i^*(\varepsilon_i, D_i) = 0, \qquad \text{if } \varepsilon_i/(\varepsilon_i + D_i) > p_j$$

respectively. Note that the above equations form each player's equilibrium strategy. This means that player i sends an FBM instantly if his relative cost $\varepsilon_i/(\varepsilon_i + D_i)$ takes values below threshold $p_j = \varepsilon_i^*/(\varepsilon_i^* + D_i^*)$, i.e., if

$$\varepsilon_i/(\varepsilon_i + D_i) < \varepsilon_i^*/(\varepsilon_i^* + D_i^*) \tag{11}$$

or

$$\varepsilon_i < D_i \cdot \xi_i^* \tag{12}$$

where $\xi_i^* = \varepsilon_i^*/D_i^*$ is the equilibrium cutoff value to be determined later. Correspondingly, player i will delay the transmission of his FBM, if his relative cost $\varepsilon_i/(\varepsilon_i + D_i)$ takes sufficiently high values, i.e., if

$$\varepsilon_i/(\varepsilon_i + D_i) > \varepsilon_i^*/(\varepsilon_i^* + D_i^*) \tag{13}$$

or

$$\varepsilon_i > D_i \cdot \xi_i^*. \tag{14}$$

Based on the same rationale and using (3), the probability p_j that player j will delay the transmission of his FBM is

$$\begin{aligned} p_j &= Pr\left\{D_j \cdot \xi_j^* < \varepsilon_j < \varepsilon_{\max}\right\} \\ &= 1 - Pr\left\{\varepsilon_{\min} < \varepsilon_j < D_j \cdot \xi_j^*\right\}. \end{aligned} \tag{15}$$

Since $p_j = \varepsilon_i^*/(\varepsilon_i^* + D_i^*) = \xi_i^*/(\xi_i^* + 1),\ i = 1, 2,\ i \neq j$, from (15), the equilibrium cutoff levels $\xi_i^*,\ i = 1, 2$ are determined from

$$\xi_i^*/(\xi_i^* + 1) = 1 - \int_{D_{\min}}^{D_{\max}} \int_{\varepsilon_{\min}}^{D_j \cdot \xi_j^*} f_D(D) f_\varepsilon(\varepsilon) dD d\varepsilon \qquad i = 1, 2,\ i \neq j \tag{16}$$

where $f_D(D)$ and $f_\varepsilon(\varepsilon)$ are the distributions related to the delay and energy cost, respectively. Thus, ξ_1^* and ξ_2^* must both satisfy (16). Therefore, if an equilibrium cutoff level exists, it is the unique solution ξ^* of (see Appendix A)

$$\xi^*/(\xi^*+1) = 1 - \int_{D_{\min}}^{D_{\max}} \int_{\varepsilon_{\min}}^{D_j \cdot \xi^*} f_D(D) f_\varepsilon(\varepsilon) dD d\varepsilon. \quad (17)$$

Then, the average probability of instant FBM transmission is

$$P_{\mathrm{FB}} = 1 - \xi^* / \left(\xi^*+1\right). \quad (18)$$

C. Extension to N Players

Let $\mathbf{N} = \{1, 2, \ldots, N\}$ and $p_i,\ i \in \mathbf{N}$, denote the probability that player i does not send an FBM instantly. In the N-player version of the game, N players having lost the same block participate in the game. Usually, the number of users in feedback suppression problems are estimated through the number of FBMs that arrive at the source [12]. In satellite networks operating above 10 GHz, the problem appears when the multicast system is under rain conditions. Then, the majority of users located within the served area suffer simultaneously from a high number of packet losses; therefore, the number of players is quite close to the total number of multicast receivers [22]. Using the same rationale with the two player game, if player i does not send an FBM, he has a normalized payoff equal to 1 and no delay, provided that at least one of the other $N-1$ players will send an FBM. If player i sends an FBM instantly, he has a payoff equal to $1-\varepsilon_i$. If all players risk and delay the transmission of their FBM, he has a payoff $1-(\varepsilon_i + D_i)$. Now let p_{-i} be the probability that none of the other players except i sends an FBM. Then

$$\pi_{\text{player } i \text{ sends FBM instantly}} = 1 - \varepsilon_i \quad (19)$$

and

$$\pi_{\text{player } i \text{ sends FBM with delay}} = p_{-i} \cdot [1 - (\varepsilon_i + D_i)] + (1 - p_{-i}) \cdot 1. \quad (20)$$

Thus, player i will send an FBM instantly if this strategy awards him higher payoff, that is

$$\pi_{\text{player } i \text{ sends FBM instantly}} > \pi_{\text{player } i \text{ sends FBM with delay}} \quad (21)$$

or

$$\varepsilon_i/(\varepsilon_i + D_i) < p_{-i}. \quad (22)$$

Hence

$$s_i^*(\varepsilon_i, D_i) = 1, \qquad \text{if } \varepsilon_i/(\varepsilon_i + D_i) < p_{-i}$$

and

$$s_i^*(\varepsilon_i, D_i) = 0, \qquad \text{if } \varepsilon_i/(\varepsilon_i + D_i) > p_{-i}.$$

Note that the above equations form each player's equilibrium strategy.

As deduced from the two-player version of the game, player i, $i \in \mathbf{N}$, will send an FBM instantly if the relative cost $\varepsilon_i/(\varepsilon + D_i)$ takes values below $p_{-i} = \varepsilon_i^*/(\varepsilon_i^* + D_i^*)$, i.e., if

$$\varepsilon_i/(\varepsilon + D_i) < \varepsilon_i^*/(\varepsilon_i^* + D_i^*) \quad (23)$$

or

$$\varepsilon_i < D_i \cdot \xi_i^* \quad i \in \mathbf{N} \quad (24)$$

where ξ_i^* is the equilibrium cutoff value to be determined. Based on (3) and (24), the probability that none of the players except player i sends an FBM is given from

$$p_{-i} = \prod_{j=1,\, j\neq i}^{N} \left[1 - Pr\left\{\varepsilon_{\min} < \varepsilon_j < D_j \xi_j^*\right\}\right]. \quad (25)$$

Since $p_{-i} = \varepsilon_i^*/\left(\varepsilon_i^* + D_i^*\right) = \xi_i^*/\left(\xi_i^*+1\right)$, the equilibrium cutoff values ξ_i^*, $i \in \mathbf{N}$, should all satisfy

$$\xi_i^*/\left(\xi_i^*+1\right) = \prod_{j=1,\, j\neq i}^{N} \left[1 - Pr\left\{\varepsilon_{\min} < \varepsilon_j < D_j \xi_j^*\right\}\right] \quad \text{for all } i \in \mathbf{N}. \quad (26)$$

If a unique equilibrium cutoff value exists, it is the unique solution ξ^* of

$$\xi^*/\left(\xi^*+1\right) = \left[1 - \int_{D_{\min}}^{D_{\max}} \int_{\varepsilon_{\min}}^{D_j \cdot \xi^*} f_D(D) f_\varepsilon(\varepsilon) dD d\varepsilon\right]^{N-1}. \quad (27)$$

Then, the average FBM transmission probability is

$$P_{\mathrm{FB}} = 1 - \left[\xi^*/\left(\xi^*+1\right)\right]^{1/(N-1)}. \quad (28)$$

From (28) it is deduced that if the number of multicast receivers is low, the probability to send an FBM instantly is high. On the other hand, as N increases, P_{FB} is reduced, the receivers (players) risk that none of the receivers will send an FBM.

D. Performance Metrics

Even though the feedback suppression problem may be effectively modeled based on game theory, it may prove inadequate, since when the population of the multicast group is large, the multicast receivers become so indifferent that none of them sends an FBM instantly.

In the feedback suppression game under consideration, the probability that none of the receivers selects the strategy to send an FBM instantly, is determined from (28), that is

$$P_{\mathrm{NFB}} = (1 - P_{\mathrm{FB}})^N = \left[\xi^*/\left(\xi^*+1\right)\right]^{N/(N-1)}. \quad (29)$$

Therefore, in this case, all users adopt the strategy to wait and then send an FBM. In a practical scenario, this strategy may be easily implemented using timers configured by the multicast receivers to expire slightly after RTT. If the timer of a receiver expires before the reception of the lost block, it sends an FBM asking for retransmission. The timer duration should be sufficient for retransmitted blocks to reach all multicast receivers and suppress their FBMs. Hence, the expected number of FBMs and the average feedback delay are given from

$$\begin{aligned} E_{\mathrm{FBM}} &= (P_{\mathrm{FB}} + P_{\mathrm{NFB}}) \cdot N \\ &= \left\{1 - \left[\xi^*/\left(\xi^*+1\right)\right]^{\frac{1}{(N-1)}} + \left[\xi^*/\left(\xi^*+1\right)\right]^{\frac{N}{N-1}}\right\} \cdot N. \end{aligned} \quad (30)$$

The average feedback delay transmitted by the receivers is determined from

$$\text{Delay} = P_{\text{FB}} \cdot + P_{\text{NFB}} \cdot \overline{\text{RTT}} = \left[\xi^* / \left(\xi^* + 1\right)\right]^{N/(N-1)} \cdot \overline{\text{RTT}} \quad (31)$$

where $\overline{\text{RTT}}$ is the average RTT. The above two performance metrics and $\overline{\text{RTT}}$ depend on the distributions $f_D(D)$ and $f_\varepsilon(\varepsilon)$ of the normalized delay and energy cost, respectively.

E. Estimating the Number of Receivers

So far, a game-theoretic feedback suppression scheme has been presented, along with appropriate performance metrics. It has been assumed that number of receivers that has failed to correctly receive a data segment is known or can be estimated. This section shows how such an estimate can be obtained based on the FBMs that arrive at the source. A similar approach to the problem of estimating the number of multicast receivers may be found in [28].

Let $\hat{E}$, $\hat{D}$ be the average number and the average delay of the FBMs returned from the receivers, respectively, after RTT, measured at the sender. Based on (30) and (31), the number of receivers that have failed to correctly receive a data segment is determined at the sender from the solution of the following system:

$$N\left(P_{\text{FB}} + (1 - P_{\text{FB}})^N\right) = \hat{E} \quad (32a)$$

$$\overline{\text{RTT}}\, P_{\text{FB}} + 2\overline{\text{RTT}}\,(1 - P_{\text{FB}})^N = \hat{D}. \quad (32b)$$

Since for large number of receivers $P_{\text{FB}} \ll 1$, the solution of the above system can be further simplified employing the approximation $(1 - P_{\text{FB}})^N \approx 1 - \text{NP}_{\text{FB}}$.

III. PERFORMANCE ANALYSIS

A. Analysis for Uniformly Distributed Costs

To examine the performance of the proposed GTFS scheme, the users residual battery power α_i is assumed to follow the uniform distribution over $(\alpha_{\min}, \alpha_{\max})$ as inferred from the fact that all STs have the same equipment and their battery is recharged at randomly selected time instants. A similar assumption is adopted in [29], where it is stated that in a mobile device the energy consumption, as well as the operation time and consequently the residual battery power follows the uniform distribution.

Also, for simplicity reasons, it is assumed that RTT delays for all users are uniformly distributed ranging from $\text{RTT}_{\min}$ to $\text{RTT}_{\max}$. Under these assumptions, (27) may be written (see Appendixes B–D) as

$$\frac{\xi^*}{\xi^* + 1} = \left[1 - \frac{\wp_1}{\varepsilon_{\min}} + \frac{\wp_1 \wp_2}{\xi^*}\right]^{N-1} \quad (33)$$

where $\wp_1$ $\wp_2$ are parameters related to energy and delay cost distributions, defined in Appendixes B and D. Then, ξ^* may be evaluated as the numerical solution of (33) and substituted into (30) and (31) to yield the expected number of FBMs and the average delay. Note that in the numerical calculations, a similar satellite network topology with that described in [22] has been employed. Specifically, Hellas Sat 2 at $39^o E$ is considered.

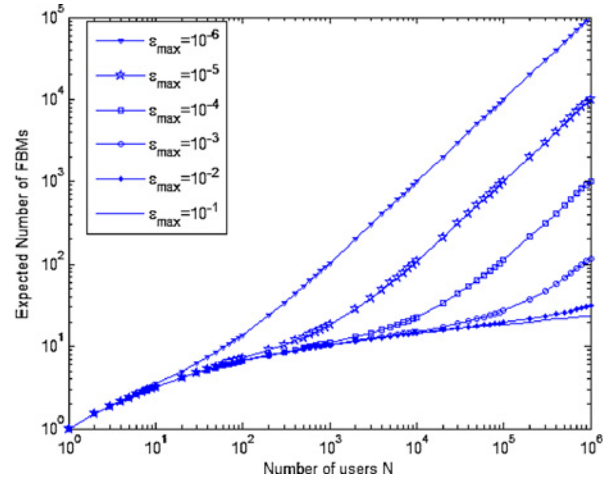

Fig. 1. Expected number of FBMs versus N for various levels of $\varepsilon_{\max}$, when the GTFS is applied ($\varepsilon_{\min} = 10^{-10}$).

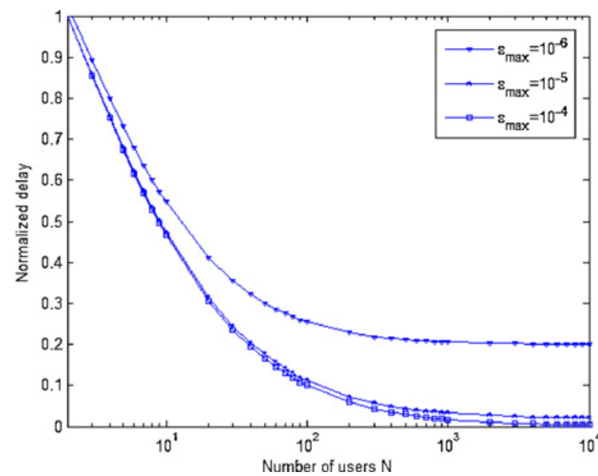

Fig. 2. Average normalized delay versus N for various levels of $\varepsilon_{\max}$ when the GTFS is applied ($\varepsilon_{\min} = 10^{-10}$).

Furthermore, RTT delays are uniformly distributed between 480 ms and 540 ms [32] and the weighting factors w_e and w_D have been taken equal to 1. The network under consideration is assumed to operate at 40 GHz, where the dominant factor impairing link performance is rain attenuation. For this reason, a dynamical rain rate field has been implemented exhibiting both spatial and temporal variations. For the simulation, the spatial and temporal variations of rain were simulated using the model presented in [33].

In Fig. 1, E_{FBM} quantifying the suppression performance of the proposed GTFS scheme is plotted for $\varepsilon_{\min} = 10^{-10}$ and various values of $\varepsilon_{\max}$. It is observed that when $\varepsilon_{\max} = 10^{-1}$, the GTFS performance is impressive limiting the expected number of FBMs below 30 for as many as 10^6 receivers. However, if $\varepsilon_{\max}$ is reduced below 10^{-4}, the suppression performance of the GTFS scheme becomes worse, since, then, the users have no incentive to send an FBM as their power has almost been exhausted. The appearance probability of the Genovese Syndrome becomes high, triggering the backup mechanism that leads to a dramatic increase in the number of FBMs.

In Fig. 2, $D_{\text{FB}}/\overline{\text{RTT}}$, that is the average delay normalized with respect to $\overline{\text{RTT}}$, is plotted versus the number of users

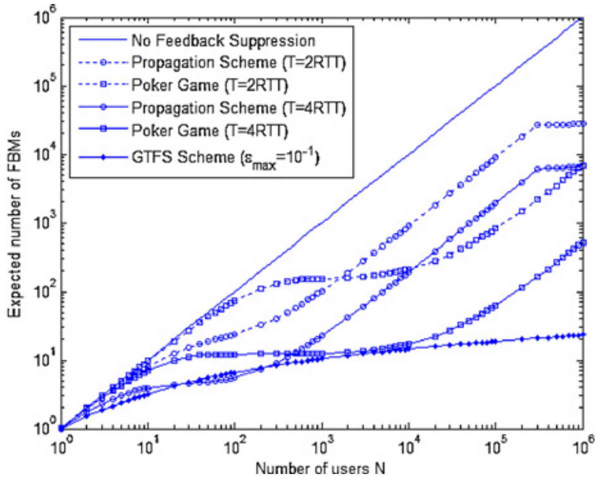

Fig. 3. Performance comparison of the GTFS scheme to the *Poker Game* scheme with λ = 10 and to the *Propagation* scheme with respect to the expected number of FBMs ($\varepsilon_{\min} = 10^{-10}$).

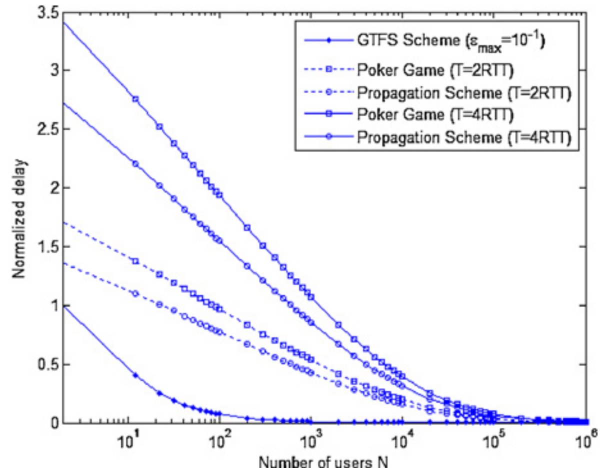

Fig. 4. Performance comparison of the GTFS scheme to the *Poker Game* scheme with λ = 10 and to the *Propagation* scheme with regard to the normalized delay for ($\varepsilon_{\min} = 10^{-10}$).

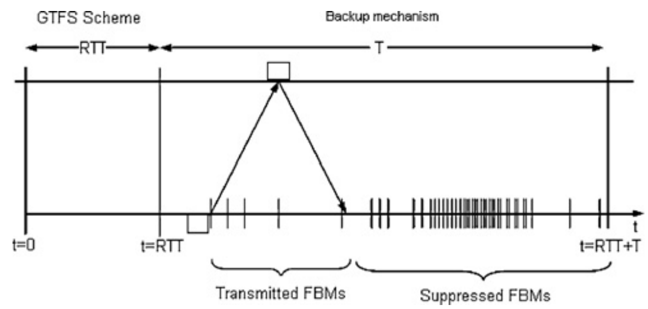

Fig. 5. Feedback suppression scheme. At t = 0, users decide whether to send an FBM or not. At t = RTT, the backup mechanism is activated, if no message has been received up to this moment.

for various values of $\varepsilon_{\max}$. For high values of $\varepsilon_{\max}$, the delay is extremely low, since the probability of sending an FBM is high. On the other hand, for low values of $\varepsilon_{\max}$, $D_{\mathrm{FB}}/\overline{\mathrm{RTT}}$ is increased since, then, the backup mechanism is activated more frequently.

Next, the proposed GTFS scheme is compared to the timer-based feedback suppression schemes presented in [21] and [22]. The key idea behind these schemes is that when a receiver detects that an FBM has been sent by another terminal, it does not transmit its own FBM. In both these schemes, it is assumed that when a receiver sends an FBM to the hub source via the satellite, all the other receivers will be able to receive it and are refrained from transmitting their own FBM. An issue arises in cases when due to signal disruptions some receivers involved do not receive the FBM. If all receivers delay their feedback transmission, feedback implosion can be avoided. The major difference between the two schemes is that in [21], the delays are random, while in [22], they are deterministic optimized under certain propagation conditions. In [21], the random delays introduced by the timer are assumed exponentially distributed over the interval $(0, T)$ following the distribution

$$f_t(t) = \begin{cases} \frac{1}{e^{\lambda}-1} \cdot \frac{\lambda}{T} e^{\frac{\lambda}{T}t}, & 0 \le t \le T \\ 0, & \text{otherwise.} \end{cases} \tag{34}$$

In the following, [21] and [22] will be referred to as *Poker Game* and *Propagation* feedback suppression schemes, respectively. From Fig. 3, it is easily observed that the proposed GTFS scheme with $\varepsilon_{\max} = 10^{-1}$ achieves a considerably better performance compared to the *Poker Game* and *Propagation* schemes with $T = 4\overline{\mathrm{RTT}}$ and λ = 10. For 10^4 receivers, the proposed scheme reduces feedback transmissions almost 15 times compared to the *Poker Game* and 60 times compared to *Propagation* scheme. The *Propagation* scheme performs slightly better than GTFS in the range of 20–200 users, while *Poker Game* performs almost equally to the proposed scheme GTFS scheme for large values of T ($T \ge 4\overline{\mathrm{RTT}}$). However, large values of T result in a dramatic increase of the transmission delay. As it can be readily observed from Fig. 4 that the proposed GTFS scheme exhibits a negligible delay for a wide range of N. On the contrary, the other two timer-based schemes cause a significant feedback latency, even when $T = 2\overline{\mathrm{RTT}}$. For instance, for $N = 10^3$, the GTFS scheme exhibits an almost zero delay, whereas the *Poker Game* and *Propagation* schemes exhibit a delay close to $0.8\overline{\mathrm{RTT}}$ and $0.7\overline{\mathrm{RTT}}$, respectively, when $T = 2\overline{\mathrm{RTT}}$ or 1.3RTT and $1\overline{\mathrm{RTT}}$ when $T = 4\overline{\mathrm{RTT}}$.

It is clear that the proposed GTFS scheme achieves a high feedback suppression and negligible delays for high values of $\varepsilon_{\max}$. However, for low values of $\varepsilon_{\max}$, its suppression performance deteriorates severely. This deterioration is significantly alleviated by combining the proposed GTFS scheme with exponential timers to implement.

B. Hybrid Game Theory Feedback Suppression Algorithms

So far, game theory has been used to model the users decision about FBM transmission. In the previous analysis, a multicast receiver selects either to send an FBM instantly or delay its transmission for RTT. A more sophisticated approach would be to combine the proposed GTFS scheme with the timer-based feedback suppression scheme presented in [12] and [13]. According to this hybrid scheme, instead of delaying the FBM transmission for a period equal to $\overline{\mathrm{RTT}}$, the users perform the following operations.

1) Schedule exponentially distributed timers t_i, $1 \le i \le N$ over the interval $(\overline{\mathrm{RTT}}, \overline{\mathrm{RTT}}+T]$, with parameters (λ, T). The selection of exponentially distributed timers is based on the fact that they offer lower feedback latency and better feedback suppression compared to other distributions such as beta and uniform. A comparative study on the performance of various distributions may be found in [12].
2) When its timer expires, a multicast receiver proceeds to the following actions.
   a) If no FBM has been received up to that moment, the receiver sends an FBM to the source requesting for retransmission.
   b) If an FBM from another receiver has already been received from another user, the receiver does not send an FBM.

The above procedure is depicted in Fig. 5. At $t = 0$, the users unilaterally decide employing game theory whether to send an FBM or not. If no FBMs have been transmitted up to $t = \mathrm{RTT}$, the backup mechanism is activated and probabilistic suppression is performed. In this case, the expected number of FBMs is given by

$$E_{\mathrm{FBM}} = P_{\mathrm{FB}} \cdot N + P_{\mathrm{NFB}} \cdot E_{\mathrm{FBM}}^{(\exp)} \tag{35}$$

where

$$E_{\mathrm{FBM}}^{(\exp)} = N \frac{e^{\lambda \frac{\overline{\mathrm{RTT}}}{T}} - 1}{e^{\lambda - 1}} - e^{\lambda \frac{\overline{\mathrm{RTT}}}{T}} \left[\left(\frac{1 - e^{-\lambda \frac{\overline{\mathrm{RTT}}}{T}}}{1 - e^{-\lambda}} \right)^N - 1 \right] \tag{36}$$

is the expected number of FBMs when exponential backup timers are employed. Details concerning the analytical calculation of $E_{\mathrm{FBM}}^{(\exp)}$ can be found in [12].

Furthermore, when the proposed hybrid GTFS-timer scheme is employed, the average delay due to feedback transmission is estimated from

$$D_{\mathrm{FB}}^{(\exp)} = P_{\mathrm{FB}} \cdot \overline{\mathrm{RTT}} + P_{\mathrm{NFB}} \cdot \left(\overline{\mathrm{RTT}} + D_{\exp} \right) \tag{37}$$

where

$$D_{\exp} = \overline{\mathrm{RTT}} \int_0^1 \left(1 - \frac{e^{\lambda m} - 1}{e^{\lambda} - 1} \right) dm \tag{38}$$

is the average delay due to feedback when the timers follow the exponential distribution [12]. Note that the basic features of the game remain unaltered. Thus, the probabilities P_{FB} and P_{NFB} are estimated again based on (28) and (29), respectively. Also, the impact of the extra delay that is imported by the hybrid GTFS scheme is captured by modifying the weighting factor of the delay cost and is taken equal $w_D = 1 + T/\overline{\mathrm{RTT}}$.

Fig. 6 shows the suppression performance of the hybrid scheme for $\varepsilon_{\max} = 10^{-1}$ for two values of T. It may be observed that for N beyond 10^3 and $T > 2\overline{\mathrm{RTT}}$, the interval size does not affect the performance of the hybrid scheme. Moreover, both the hybrid and the GTFS schemes exhibit a similar performance. This should be expected, since for high values of $\varepsilon_{\max}$, the GTFS scheme exhibits an excellent suppression performance. The performance improvement of the proposed hybrid suppression scheme over the *Poker Game* and the *Propagation* schemes is significant. For example, when $N = 10^5$ and $T = 2\overline{\mathrm{RTT}}$, the hybrid algorithm improves the suppression performance more than 100 times over the *Poker Game* and 800 over the *Propagation* scheme.

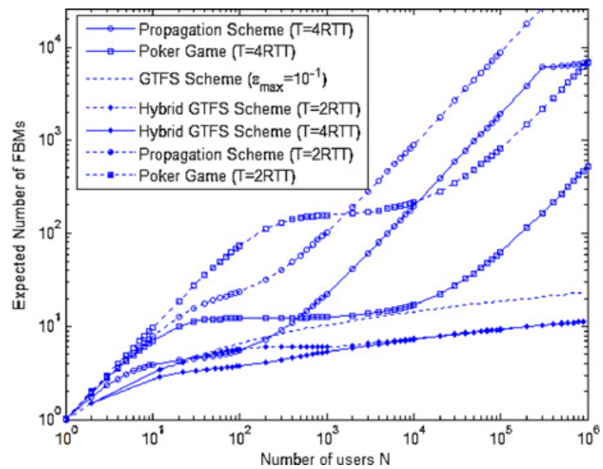

Fig. 6. Performance comparison of the hybrid suppression scheme to the *Poker Game* scheme with $\lambda = 10$ and to the *Propagation* scheme with regard to the expected number of FBMs ($\varepsilon_{\max} = 10^{-1}$, $\varepsilon_{\min} = 10^{-10}$).

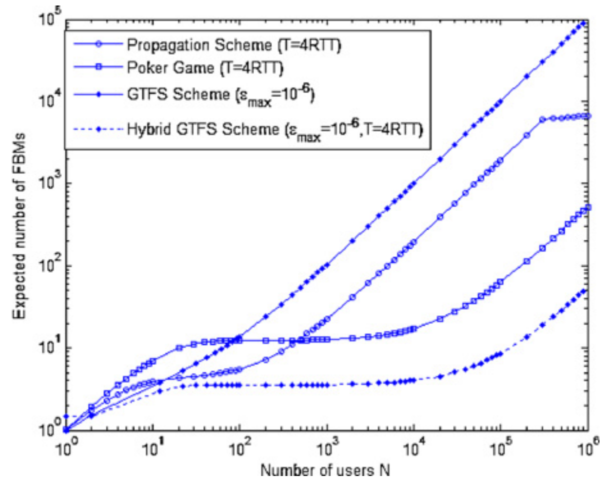

Fig. 7. Performance comparison of the hybrid suppression scheme to the *Poker Game* scheme with $\lambda = 10$ and to the *Propagation* scheme with regard to number of FBMs ($\varepsilon_{\max} = 10^{-6}$, $\varepsilon_{\min} = 10^{-10}$.

As previously mentioned, for very low values of $\varepsilon_{\max}$, the performance of the GTFS scheme is poor. In this case, the hybrid scheme performs considerably better. This is shown in Fig. 7, where for 10^5 receivers and $T = 4\mathrm{RTT}$, the hybrid scheme keeps E_{FBM} below 10. On the other hand, the *Poker Game* scheme with $T = 4\overline{\mathrm{RTT}}$ and $\lambda = 10$ keeps E_{FBM} below 35. Another interesting observation is that for $N < 80$, the GTFS scheme performs better than the *Poker Game* scheme with $T = 2\overline{\mathrm{RTT}}$ and $\lambda = 10$ and, at the same time, its latency is very low, as can be observed from Fig. 4.

Finally, in Fig. 8, the proposed hybrid scheme is compared with the *Poker Game* and *Propagation* schemes in terms of the normalized delay. For low values of $\varepsilon_{\max}$ and $N > 300$, it is clear that the hybrid scheme exhibits delays that are close to zero. For higher values of $\varepsilon_{\max}$, the delays are increased, since

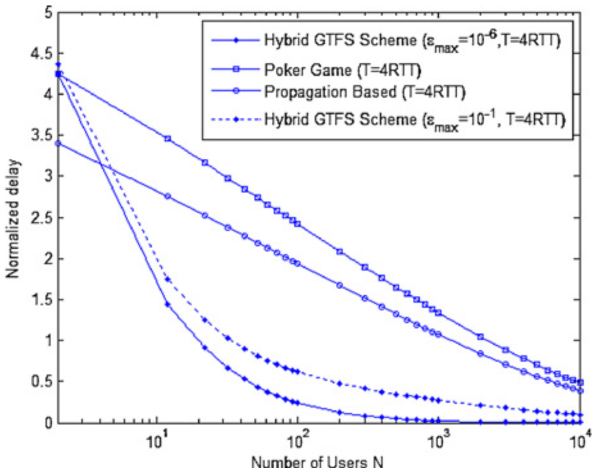

Fig. 8. Expected feedback latency of the hybrid, *Poker* and *Propagation* suppression schemes (T = 4RTT, λ = 10, $\varepsilon_{\max} = 10^{-1}, 10^{-6}$, $\varepsilon_{\min} = 10^{-10}$).

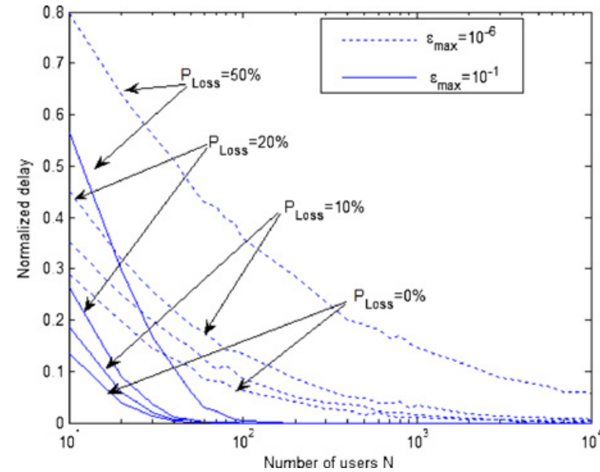

Fig. 10. Expected feedback latency for various levels of $P_{\mathrm{FBM}}^{(\mathrm{Loss})}$ (λ = 10, $\varepsilon_{\max} = 10^{-1}, 10^{-6}, \varepsilon_{\min} = 10^{-10}$).

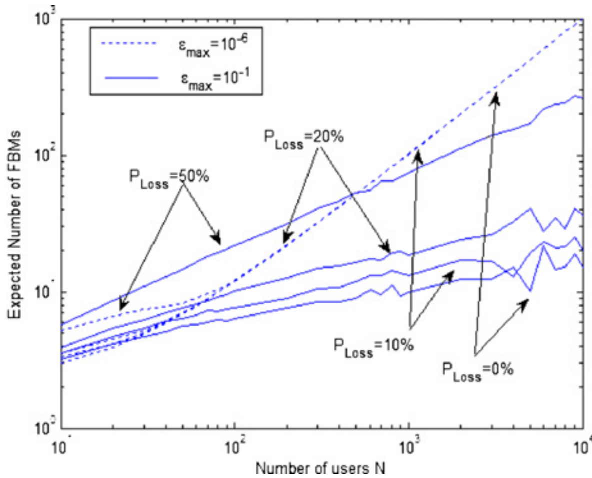

Fig. 9. Expected number of FBMs of the GTFS scheme for various levels of $P_{\mathrm{FBM}}^{(\mathrm{Loss})}$ (λ = 10, $\varepsilon_{\max} = 10^{-1}, 10^{-6}, \varepsilon_{\min} = 10^{-10}$).

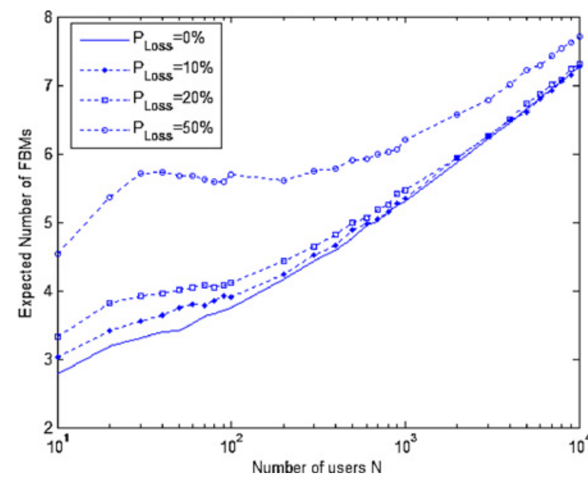

Fig. 11. Expected number of FBMs for the hybrid scheme for various levels of $P_{\mathrm{FBM}}^{(\mathrm{Loss})}$ (λ = 10, $\varepsilon_{\max} = 10^{-1}, \varepsilon_{\min} = 10^{-10}$).

the backup timers are activated more frequently. Nevertheless, even in this case, the hybrid scheme performs significantly better compared to the other two schemes.

IV. Impact of Loss of FBMs

In this section, the impact of FBM losses on the performance of the proposed feedback suppression schemes is examined. The results have been derived from MATLAB simulations after simulating 10 000 feedback rounds with parameters $\lambda = 10$ and $\varepsilon_{\min} = 10^{-10}$.

In Fig. 9, the expected number of FBMs of the GTFS scheme has been plotted versus the number of receivers for various levels of FBM loss probabilities, $P_{\mathrm{Loss}}^{(\mathrm{FBM})}$, and $\varepsilon_{\max}$. When $\varepsilon_{\max} = 10^{-1}$, $P_{\mathrm{Loss}}^{(\mathrm{FBM})} = 10\%$ or 20%, the number of FBMs is slightly increased compared to the no FBM loss case. On the contrary, when $P_{\mathrm{Loss}}^{(\mathrm{FBM})} = 50\%$, the number of FBMs is considerably increased. The reason for this behavior is that for high values of $\varepsilon_{\max}$, the GTFS scheme achieves high suppression ratios. Therefore, when $P_{\mathrm{Loss}}^{(\mathrm{FBM})}$ is high, the probability that all FBMs are lost during transmission is significant. Hence, the backup mechanisms of all receivers are activated more frequently. However, for $\varepsilon_{\max} = 10^{-6}$, the expected number of FBMs is not affected by the increase of $P_{\mathrm{Loss}}^{(\mathrm{FBM})}$. It is observed that the all curves coincide since the energy resources are scarce and the backup mechanisms are activated more frequently. In Fig. 10, the normalized delay of the GTFS scheme is plotted versus the number of receivers for various levels of $P_{\mathrm{Loss}}^{(\mathrm{FBM})}$. For low values of $P_{\mathrm{Loss}}^{(\mathrm{FBM})}$, it is clear that the GTFS scheme exhibits delays that are close to zero. For higher values of $P_{\mathrm{Loss}}^{(\mathrm{FBM})}$, the delays are increased, since the backup timers are activated more frequently.

As opposed to the GTFS scheme, the hybrid scheme proves robust against high levels of $P_{\mathrm{Loss}}^{(\mathrm{FBM})}$. This is depicted in Fig. 11, from where it is observed that applying the hybrid scheme for 10^4 receivers, $\lambda = 10$ and T = 4RTT, the expected number of FBMs is limited below 10. The reason behind this behavior is that when the exponential backup mechanism is activated, even if the FBM from the user whose timer has expired first is lost, the FBM from the next expired timer that is not lost imposes feedback suppression.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

V. CONCLUSION

In this paper, a novel feedback suppression scheme for reliable multicast services to a large number of users has been presented. For the first time, the feedback suppression problem was formulated using game theory with inaccurate information. Having as inputs its residual battery supply and the number of multicast receivers, each user unilaterally decides whether to send an FBM or not. When their number is high, multicast receivers behave as apathetic human beings thus avoiding sending FBMs. If no FBMs are transmitted, within a certain time period, backup mechanisms are activated to ensure reliability. The performance of the proposed scheme with regard to feedback suppression has been investigated analytically. The simulations performed revealed that the proposed game-theory-based scheme exhibit an excellent performance if the messages are transmitted with low packet loss rates and the receivers have sufficient battery power. To cover the rest of the cases, a hybrid game theory–timer-based feedback suppression scheme has been introduced that possesses an inherent backup mechanism. Both proposed algorithms outperform the *Poker Game* and the *Propagation* schemes, limiting the number of FBMs to a minimum, while at the same time the delay is kept near zero.

APPENDIX A
GRAPHICAL SOLUTION OF THE EQUILIBRIUM POINT

Let $c_i = \varepsilon_i/(\varepsilon_i + D_i)$ for short. Since $D_i > 0$, it is clear that $\varepsilon_i/(\varepsilon_i + D_i) < 1$. Equation (16) then becomes

$$c_i^* = 1 - F_{cj}(c_j^*) \tag{39}$$

$$c_j^* = 1 - F_{ci}(c_i^*) \tag{40}$$

where F_{ci} represents c_is cumulative distribution function over $[c_{\min}, c_{\max}]$ with $c_{\max} < 1$ because $c_i < 1$. Equation (38) gives user is best response to user js equilibrium strategy, while (39) gives user js best response to user is equilibrium strategy. Thus, user js best response is

$$R_j(c_i) = 1 - F_{ci}(c_i). \tag{41}$$

Similarly, user is best response is expressed as follows:

$$R_i(c_j) = 1 - F_{cj}(c_j). \tag{42}$$

Since F_{ci} is a nondecreasing function, R_i and R_j are both nonincreasing. These two best-response intersection functions intersect only *once*, at the equilibrium quantity pair (c_i^*, c_j^*) and due to symmetry $c_i^* = c_j^*$.

A second way to solve the problem is to apply the process of iterated elimination of strictly dominated strategies, while a third way is to solve the problem algebraically. Both approaches yields a unique solution (c_i^*, c_j^*) [34].

APPENDIX B
DISTRIBUTION OF THE NORMALIZED ENERGY COST

If the residual battery power α_i follows the uniform distribution in the range $(\alpha_{\min}, \alpha_{\max})$, that is

$$f_\alpha(\alpha_i) = \frac{1}{\alpha_{\max} - \alpha_{\min}}, \quad \alpha_{\min} < \alpha_i < \alpha_{\max} \tag{43}$$

the normalized energy cost $\varepsilon_i = w_e dE/\alpha_i$ follows the distribution

$$f_\varepsilon(\varepsilon_i) = f_\alpha(\alpha_i)\left|\frac{d\alpha_i}{d\varepsilon_i}\right| = \frac{\wp_1}{\varepsilon_i^2}, \quad \varepsilon_{\min} < \varepsilon_i < \varepsilon_{\max} \tag{44}$$

where $\wp_1 = w_e dE/(\alpha_{\max} - \alpha_{\min})$.

APPENDIX C
DISTRIBUTION OF THE DELAY

If RTT_i follows the uniform distribution in the range $(\mathrm{RTT}_{\min}, \mathrm{RTT}_{\max})$, that is

$$f_{\mathrm{RTT}}(\cdot) = \frac{1}{\mathrm{RTT}_{\max} - \mathrm{RTT}_{\min}}, \quad \mathrm{RTT}_{\min} < \mathrm{RTT}_i < \mathrm{RTT}_{\max} \tag{45}$$

the normalized delay cost $D_i = w_d \mathrm{RTT}_i$ follows the distribution

$$f_D(D_i) = \frac{1}{D_{\max} - D_{\min}}, \quad D_{\min} < D_i < D_{\max}. \tag{46}$$

APPENDIX D
CALCULATION OF THE EQUILIBRIUM CUTOFF VALUE

Substituting (40) and (43) into (27) yields

$$\frac{\xi^*}{\xi^* + 1} = \left[1 - \int_{D_{\min}}^{D_{\max}} \frac{1}{D_{\max} - D_{\min}} \left(\frac{1}{\varepsilon_{\min}} - \frac{1}{D\xi^*}\right) dD\right]^{N-1} \tag{47}$$

or

$$\frac{\xi^*}{\xi^* + 1} = \left[1 - \frac{\wp_1}{\varepsilon_{\min}} + \frac{\wp_1\wp_2}{\xi^*}\right]^{N-1} \tag{48}$$

where $\wp_2 = \left(\frac{\ln D_{\max} - \ln D_{\min}}{D_{\max} - D_{\min}}\right)$.

REFERENCES

[1] K. Obraczka, "Multicast transport protocols," *IEEE Commun. Mag.*, vol. 36, no. 1, pp. 94–102, Jan. 1998.

[2] J. W. Atwood, "A classification of reliable multicast protocols," *IEEE Netw.*, vol. 18, no. 3, pp. 24–34, May–Jun. 2004.

[3] B.-S. Kim, S. W. Kim, and R. L. Ekl, "OFDMA-based reliable multicasting MAC protocol for WLANs," *IEEE Trans. Veh. Tech.*, vol. 57, no. 5, pp. 3136–3145, Sep. 2008.

[4] W.-H. Kuo and J.-F. Lee, "Multicast recipient maximization in IEEE 802.16j WiMAX relay networks," *IEEE Trans. Veh. Tech.*, vol. 59, no. 1, pp. 335–343, Jan. 2010.

[5] M. P. Anastasopoulos, A. V. Vasilakos, and P. G. Cottis, "An autonomic framework for reliable multicast: A game theoretical approach based on social psychology," *ACM Trans. Autonomous Adap. Syst.*, vol. 4, no. 4, pp. 1–23, Nov. 2009.

[6] M. Grossglauser, "Optimal deterministic timeouts for reliable scalable multicast," in *Proc. Infocom*, Mar. 1996, pp. 1425–1432.

[7] S. Paul, K. K. Sabnani, J. C. Lin, and S. Bhattacharyya, "Reliable multicast transport protocol (RMTP)," *IEEE J. Sel. Areas Commun.*, vol. 15, no. 3, pp. 407–421, Apr. 1997.

[8] B. Whetten and G. Taskale, "An overview of reliable multicast transport protocol II," *IEEE Netw.*, vol. 14, no. 1, pp. 37–47, Jan. 2000.

[9] *Reliable Multicast Transport Working Group Charter* [Online]. Available: http://www.ietf.org/html.charters/rmt-charter.html

[10] H. Holbrook, S. Singhal, and D. Cheriton, "Log-based receiver-reliable multicast for distributed interactive simulation," in *Proc. ACM SIGCOMM*, vol. 25, no. 4. Oct. 1995, pp. 328–341.

[11] M. Baysan and K. Sarac, "Cluster based approaches for end-to-end complete feedback collection in multicast performance," in *Proc. IEEE IPCCC*, Apr. 2006, pp. 10–12.

[12] J. Nonnenmacher and E. W. Biersack, "Scalable feedback for large groups," *IEEE/ACM Trans. Netw.*, vol. 7, no. 3, pp. 375–386, Jun. 1999.

[13] S. Floyd, V. Jacobson, C.-G. Liu, S. McCanne, and L. Zhang, "A reliable multicast framework for light-weight sessions and application level framing," *IEEE/ACM Trans. Netw.*, vol. 5, no. 6, pp. 784–803, Dec. 1997.

[14] J. Crowcroft and K. Paliwoda, "A multicast transport protocol," in *Proc. ACM SIGCOMM*, Aug. 1988, pp. 247–256.

[15] S. Wu, S. Banerjee, and X. Hou, "Performance evaluation and comparison of multicast feedback control mechanisms," *Simulation*, vol. 82, no. 5, pp. 345–362, 2006.

[16] Y. Bi, L. X. Cai, X. Shen, and H. Zhao, "Efficient and reliable broadcast in intervehicle communication networks: A cross-layer approach," *IEEE Trans. Veh. Tech.*, vol. 59, no. 5, pp. 2404–2417, Jun. 2010.

[17] Y.-C. Lai, P. Lin, Y.-B. Lin, and L.-T. Chang, "A file repair scheme for UMTS MBMS service," *IEEE Trans. Veh. Tech.*, vol. 57, no. 6, pp. 3746–3756, Sep. 2008.

[18] C. Papadopoulos and G. Parulkar, "Implosion control for multipoint applications," in *Proc. 10th IEEE Workshop Comput. Commun.*, Sep. 1995, pp. 1–11.

[19] M. Koyabe and G. Fairhurst, "Reliable multicast via satellite: A comparison survey and taxonomy," *Int. J. Sat. Commun.*, vol. 19, pp. 3–28, Jan.–Feb. 2001.

[20] G. Akkor, M. Hadjitheodosiou, and J. S. Baras, "Transport protocols in multicast via satellite," *Int. J. Sat. Commun.*, vol. 22, no. 6, pp. 611–627, Nov.–Dec. 2004.

[21] S. Cho and I. F. Akyildiz, "A poker-game-based feedback suppression algorithm for satellite reliable multicast," in *Proc. IEEE GLOBECOM*, vol. 3. Nov. 2002, pp. 2930–2934.

[22] M. P. Anastasopoulos, A. D. Panagopoulos, and P. G. Cottis, "A feedback suppression algorithm for reliable satellite multicast based on spatial-temporal prediction of the satellite channel," *Int. J. Sat. Commun. Netw.*, vol. 27, no. 2, pp. 117–139, Mar.–Apr. 2009.

[23] E. Ichihara, K. Kikuchi, T. Tsuchida, K. Kawazoe, and H. Kazama, "Reliable IP-multicast protocol for bi-directional satellite communication systems," in *Proc. AIAA ICSSC*, vol. 102, no. 666. Apr. 2003, pp. 13–18.

[24] G. Akkor, J. S. Baras, and M. Hadjithedosiou, "A feedback implosion suppression algorithm for satellite reliable multicast," in *Proc. IEEE GLOBECOM*, vol. 7. Dec. 2003, pp. 3765–3769.

[25] G. Akkor, J. S. Baras, and M. Hadjithedosiou, "A multiple subset sum formulation for feedback implosion suppression over satellite networks," in *Proc. IEEE GLOBECOM*, vol. 6. Dec. 2005, pp. 3226–3230.

[26] D. Fudenberg and J. Tirole, *Game Theory*. Cambridge, MA: MIT Press, 1991.

[27] M. Luby, L. Vicisano, J. Gemmell, L. Rizzo, M. Handley, and J. Crowcroft "The use of forward error correction (FEC) in reliable multicast," document RFC-3453, Network Working Group, Dec. 2002.

[28] J. Nonnenmacher, "Reliable multicast to large groups," Ph.D. dissertation, Sec. Commun. Syst., Ecole Polytech. Federale Lausanne, Lausanne, Switzerland, Jul. 1998.

[29] J. K. Kim, H. J. Siegel, A. A. Maciejewski, and R. Eigenmann, "Dynamic resource management in energy constrained heterogeneous computing systems using voltage scaling," *IEEE Trans. Parallel Distrib. Syst.*, vol. 19, no. 11, pp. 1145–1457, Nov. 2008.

[30] D. K. Petraki, M. P. Anastasopoulos, and P. G. Cottis, "Dynamic resource allocation for DVB-RCS networks," *Int. J. Sat. Commun. Netw.*, vol. 26, no. 3, pp. 189–210, Jun. 2008.

[31] F. Alagoz and G. Gur, "Energy efficiency and satellite networking: A holistic overview," *Proc. IEEE*, vol. 99, no. 11, pp. 1954–1979, Nov. 2011.

[32] S. D. Ilcev, *Global Mobile Satellite Communications: For Maritime, Land and Aeronautical Applications*. New York: Springer, 2005.

[33] B. C. Gremont and M. Filip, "Spatio-temporal rain attenuation model for application to fade mitigation techniques," *IEEE Trans. Antennas Propag.*, vol. 52, no. 5, pp. 1245–1256, May 2004.

[34] R. Gibbons, *A Primer in Game Theory*. London, U.K.: Pearson, 1992.

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