Performance Analysis of a Rate-Adaptive Bandwidth Allocation Scheme in 5G Mobile Networks

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***Abstract*—The efficient support of the massive device transmission is challenging in Machine-to-Machine (M2M) communications. A large number of devices activate transmissions within a short period of time in M2M communications, which in turn cause high radio access congestions and severe wireless access medium delay. In this context, this work proposes a hybrid MAC approach, based on the well-known ALOHA protocol, and intended to be applied in 5G mobile networks. The topology changes dynamically in the proposed rate-adaptive ALOHA scheme, whereas the bandwidth of a channel is utilized effectively aiming to improve the overall performance of the M2M mobile environment. A random distribution model was exploited during the conducted experiments in order to perform a systematic evaluation of bidirectional communication within a 5G mobile environment. The major contribution of the proposed scheme is the improvement of the network throughput as multiple connections are possible. The experimental results indicate the scheme's efficiency by offering high throughput as opposed to the delay variations between packets, while the proposed scheme aims at maximizing the efficiency of resource exchange between mobile peers.**

Keywords—5G mobile networks; rate-adaptive scheme; adaptive MAC; rate-adaptive bandwidth allocation; performance evaluation

I. Introduction

Since the data burst and the emerging multimedia traffic will occur in the 5G mobile networks, adaptive bandwidth allocation schemes are imperative in ensuring the QoS (Quality of Service). In this context, this paper emphasizes the importance of a rate-adaptive bandwidth allocation scheme, which is based on the well-known ALOHA protocol and is intended to be applied in 5G mobile networks. Rate adaptation constitutes a technique for dynamically switching data rates to match the channel conditions, aiming to give the optimum throughput and has been adopted in numerous research approaches [1]–[4]. In addition, studies based on the ALOHA protocol [5] indicated that the overall channel utilization was below 18% and, therefore, it was considered very low. The channel utilization can be increased by 35% with slotted ALOHA [6] as the time is divided into slots and the nodes may only start transmitting at the beginning of a slot, reducing the probability of packet collision. Hence, these protocols are not the appropriate ones to be applied in the 5G mobile networks and they do not solve the problem of hidden nodes, which increases the probability of a collision. Due to this problem, this work elaborates on the implementation of a rate-adaptive bandwidth allocation scheme in the 5G mobile environment. Furthermore, the simulation results indicate that the proposed scheme smoothly adapts to network changes and improves the performance, utilizing network bandwidth.

Since the mobile terminals are becoming highly computationally capable devices, which can support more complex functionalities, 5G is expected to satisfy the QoS [7] and the rate requirements set by forthcoming applications, like wireless broadband access, Multimedia Messaging Service (MMS), video chat, mobile TV, Digital Video Broadcasting (DVB) and other services that utilize bandwidth [8], [9]. Furthermore, since no central-control device exists, each node behaves as a router forwarding data unrelated to its own use and resulting to an improved scalable network. Hence, the assumptions that were considered when conducting the simulation experiments in the 5G mobile approach, are based on the fact that the nodes act like routers, there is no centralized infrastructure and there are also issues regarding the dynamic network topology.

Despite the positive characteristics of the 5G mobile networks [10]–[13], the challenges being considered are the bandwidth utilization, mobility and fading [14]–[18]. The improvement of the network throughput [19], where multiple connections are possible, is also researched. This paper proposes and models the mechanisms utilized by a hybrid MAC approach, based on the well-established ALOHA protocol, intended to be applied in the 5G mobile context and the simulation results demonstrate that the exploited rate-adaptive bandwidth allocation scheme utilizes the bandwidth of a channel effectively and the overall performance of the M2M mobile environment is improved using the threshold-based and probabilistic rate selection scheme.

The structure of this paper is organized as follows: Section II presents related work approaches and the research motivation, whereas the proposed rate-adaptive bandwidth allocation scheme is described in Section III. Section IV shows the exploited simulation models and Section V presents the performance evaluation results. Finally, Section VI concludes the paper highlighting key findings of the simulation results.

II. Related Work and Research Motivation

A number of research efforts have been devoted considering the bandwidth allocation issues. In this context, Li et al. in [3] introduce a novel adaptive bandwidth allocation scheme, aiming to estimate the changing traffic parameters through local on-line estimation, and propose the use of a probabilistic control policy. The simulation results show that the proposed scheme can guarantee the predetermined call dropping probability under changing traffic conditions. On the other hand, Cao and Zegura in [20] examine an application-layer performance measure approach in the context of bandwidth allocation for an available bit rate service. In this work, the proposed scheme intends to provide good application-layer service to a wide diversity of applications sharing available bandwidth. Furthermore, Oliveira et al. in [21] propose an admission control scheme based on adaptive bandwidth reservation to provide QoS guarantees for multimedia traffic carried in high-speed wireless cellular networks. The simulation results indicate small hand-off dropping probability and high bandwidth utilization. On the contrary, authors in [22] elaborate on the key properties that a dynamic bandwidth allocation scheme should have and propose bandwidth allocation criteria, which depend on the residual work of on-going transfers. In this paper, the analysis indicates that the allocating bandwidth in this fashion can improve the user perceived average bit transmission delay by up to 70% at 80% traffic load over traditional approaches.

Authors in [6] analyze the efficiency of the slotted ALOHA protocol in multi-hop environment, indicating that it is always possible to optimize the network efficiency by properly setting the required rate for a given packet density. Additionally, this work shows the slotted ALOHA protocol can be implemented as a two-state system. More specifically, the node is in *Free State* in case that the previous transmission was successful; otherwise it is in *Backlogged State*. The node transmits data with probability *1* in *Free State*, while the transmission probability p is considered in *Backlogged State*. A generalization of the above protocol is presented in [23], aiming to allow a node to vary the probability with which it transmits data within the *Free State*. Another related research approach in [24] attempts to improve the performance by adopting an exclusion mechanism that prevents mobile devices, which are close, from transmitting at the same time. Furthermore, the proposed MAC protocol in [24], so-called spatial reuse, aims to avoid simultaneous neighboring transmissions and allow those happening in different parts of the network in order to prevent collisions. Authors in [25] introduce a new protocol, called *Smart-ALOHA*, where the nodes are equipped with adaptive array smart antennas. Narrowing in, the protocol relies on the ability of the antenna and the direction-of-arrival (DOA) algorithms to identify the direction of transmitter, maximizing the signal-to-interference ratio (SINR) at the receiver. Despite the positive results and the improved performance, the limited choice of smart antennas in the marketplace makes the protocol less feasible to adapt to the market. On the contrary, the multi-frame reservation ALOHA is introduced in [26], which offers several consecutive frames instead of having only one access frame, ending up to the conclusion that the average delay produced is lower than the reservation ALOHA. Authors in [27] argue that the MAC protocol can affect the performance of the routing protocol. A modified version of flooding algorithm for route finding [28] is adopted in our simulation experiments and the results indicate that the routing is improved using the rate-adaptive bandwidth allocation scheme, confirming the correctness of the argument in [27].

Finally, channel conditions may vary rapidly over time due to signal fading, distance from source, collisions from simultaneous transmissions and interference. The rate adaptation consists of two functionalities, which are the channel quality estimation and the rate selection [29], [30]. Issues that arise from channel quality estimation have to do with the metrics that should be the indicators of the channel quality (SINR, path loss, fading, bit error rate, signal strength) and whether the predictions should be long or short-term. This work is based on the rate adaptation under predefined conditions that are discussed thoroughly in Section III.

III. Rate-Adaptive Bandwidth Allocation Scheme

The proposed rate-adaptive bandwidth allocation scheme aims to allocate more rate-bandwidth to transmissions, which are close to be interrupted due to mobility, within the 5G mobile context. The rate adaptation schemes estimate the current channel condition based on some matrices in order to switch data rates [29]–[31]. Most of these schemes require the use of request-to-send/clear-to-send (RTS/CTS) [32]. In addition to the above protocols, which try to adapt the rate in single channel communication, our research approach focuses on MAC level, where two or more transmitters share common media. Limiting channel access to some nodes results in higher access probability to some other nodes and, therefore, acceleration of traffic regulation and rate adaptation, which may have a huge impact in the overall packet delivery ratio, especially in a high density environment where multiple connections are accomplished through the same link. In the most common rate-adaptive protocols, the mechanisms for channel quality estimation and rate adaptation are located on the sender [33]. Holland et al. in [29] present the rate-adaptive Receiver Based Auto Rate (RBAR) protocol where the above mechanisms are located on the receiver. The sender might act like receiver and vice versa since multiple links connect different parts of network, passing from the same node. For example, we assume a link that passes from the F, H and B (shown in Fig. 1) at the same period when G tries to transmit to H. Since the link is shared, there should be a MAC that coordinates and synchronizes the above transmissions. This study suggests that rate-adaptation mechanisms should be located and synchronized on both sender and receiver.

The proposed rate-adaptive bandwidth allocation scheme incorporates the link quality estimation, which is based on the signal density reduction due to path loss exponent [29]. The poorer the signal density is, the greater the distance is between the sender and the receiver, resulting in higher probability of communication channel breakdown that is caused by mobility. On the other hand, the rate-adaptive bandwidth allocation approach suggests higher rate-bandwidth allocation for the links that are close to breakdown. More specifically, each packet carries a constant acknowledgment (calculated from previous successful delivery), which is received after successful transmission defining the total number of hops that need to travel to the destination. Once the packet travels at each hop, the number is added to hop priority that determines access probability. The performance evaluation analysis conducted in this work demonstrates that the rate-adaptive bandwidth allocation scheme (RA-ALOHA) outperforms R-ALOHA with less delay and more successful packet delivery ratio. Regarding the rate selection algorithm, a function is used to calculate the priority gained by nodes as the higher priority indicates higher rates [34].

$$Np = \sum_{i=1}^{n} h + L + Tr \tag{1}$$

$$\delta(Np) = Np(t) - Np(t-1) \tag{2}$$

where Np is the node priority that determines the rate selection, n is the number of packets waiting in a buffer, h is the total number of hops to reach destination for packet n calculated from previous successful delivery, L is the priority gained by signal quality. In this paper, the ratio between the current transmission distance (Td) to maximum possible distance ($Tmax$) is also calculated [35].

$$R = \frac{Td}{T\max}, \forall R > 0.90 \tag{3}$$

According to equation (3), if R is greater than a threshold, then $L = 1$. In a threshold scheme, the rate is chosen by comparing the link strength against the threshold (usually a constant). If the inequality is fulfilled, a suitable rate is chosen. For example, once hop A (shown Fig. 1) transmits packets to hop B at distance 80 m ($Td = 80$) and the maximum possible distance at which transmissions are feasible is 100 m ($Tmax = 100$), we get $R = 0.80$. Considering this scenario, if threshold is less than 0.80 for hop A, then $L = 1$, which shows greater Np for A and, therefore, higher priority. Throughout our simulation experiments, the threshold is set to 0.90 that corresponds to 90% of the maximum transmission distance. Furthermore, Tr expresses the transmission retries and the node gets higher priority for each ineffective retry. The following pseudocode demonstrates the procedure taken by a node (sender) based on the proposed rate-adaptive bandwidth allocation scheme.

iterate over all neighbors

if neighbor is transmitting or Np < neighborNp

then enter waitingState

else enter transmittingState

transmittingState:

  send all packets waiting in the buffer

  set Np to zero

waitingState:

  iterate over all packets in the buffer:

  add packet total hops counter to Np

  calculate the distance between this node and packet next hop

  if R greater than a threshold (threshold = 0.90)

  then increase Np by δ(Np) (14)

increase Np by δ(Np) (15)

Considering the equation (1) and according to the presented pseudocode, Np is the weightiest variable located on each hop that has immediate impact to the rate adaptation of the proposed bandwidth allocation scheme. Np is completely dependent to neighbor values when authorization is given to access channel, whereas it also determines whether a node has the authorization to access medium. Relatively greater values of Np designate higher probability of sending data and, hence, higher transmission rates. Prior to channel access, each node checks whether there is any neighbor (other hops within transmission range) that transmits data. If there is neighbor that transmits data, it enters the `waitingState` and retries on next slot, otherwise it compares its Np variable against neighbors' variables. In case that the Np variable is greater than the *neighborNp*, then channel access is accomplished. Each hop's Np variable is increased (i.e. $\delta(Np) > 0$) under three conditions: 1) there is unsuccessful attempt to access media, 2) the distance between the current and next hop is greater than a predefined value and 3) once a hop receives packet, the `total_hops_to_destination` variable of the packet is added to Np. This mechanism does not cover the hidden terminal problem; however the receiver (that sees the hidden terminal) and the sender should have synchronized rate adaptation mechanisms.

Fairness is another feature that is considered in this work, as once a node enters the `waitingState` (i.e. unsuccessful attempt to access media), a higher priority for the next try is set (as shown in line 14 of the pseudocode). Fairness can be achieved by a scheduler, which is either overlaid on the top of the MAC layer or at the MAC layer itself [36]. From a short-term viewpoint, the rate-adaptive bandwidth allocation scheme might seem to cause unfairness, however it improves the longterm fairness. Nodes in long distance between each other communicate under a higher priority (as shown in line 15 of the pseudocode) in comparison to the rest of the nodes in the network. Henceforth, long waiting times contribute to a higher probability to access the channel. Mobility is another influential metric as the higher the node speed is, the better priority is gained. Issues that might arise are node speed estimation techniques that could be temporary considered as constant. Two possible scenarios that occur in different parts of the network and reveal how the rate-adaptive bandwidth allocation scheme adapts to such cases are demonstrated in Fig. 1. Case (a) indicates a scenario where F, G and K nodes try to gain access to H. Node K is not visible to F (i.e. hidden terminal problem) and, thus, H can decide which node should be able to transmit first. Hence, the rate-adaptive mechanism is active on the receiver. Additionally, F gets access priority since it has longer distance to H than K to H. The colors and shapes identify the last action taken by the node. More specifically, the green squares point out that the node received and forwarded data packet that was not intended for it. On the contrary, the yellow cycles and orange squares demonstrate that the node received acknowledgment and data packet, respectively. The procedure in this scenario shows the importance of the rate adaptation mechanism to be placed in both sender and receiver.

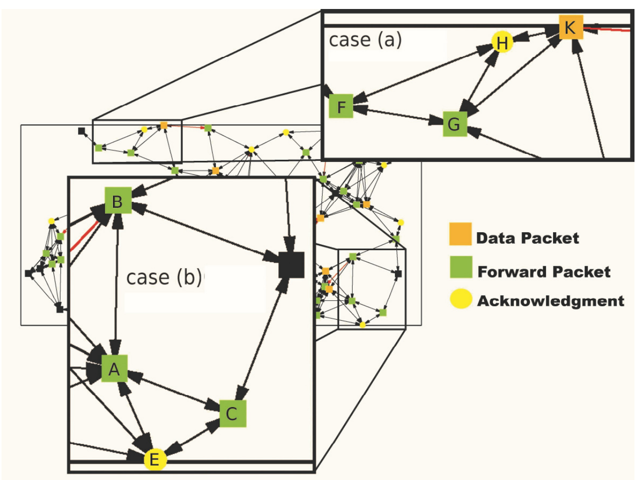

Fig. 1. Case (a): F, G and K transmit data to H. Case (b): A transmits data to B and C to E.

Regarding the scenario in case (b), A and C sent RTS to B and E, respectively. As the distance between A and B is considered longer than the one between C and E, only node A receives CTS due to the high probability of interference that is caused from simultaneous transmissions of A and C.

IV. Simulation Models Exploitation

In this section, the models that were exploited throughout our simulations are presented, which intend to compare the rate-adaptive bandwidth allocation scheme over the conventional reservation ALOHA (R-ALOHA) [37]. This comparison aims to examine the performance and the adaptive scaling of the proposed scheme. The simulations were performed using the Sinalgo simulator [38], exploiting some modules of the work presented in [39], [40] and providing an excellent framework for network algorithms evaluation. Furthermore, the hops use Constant Bit Rate (CBR) to generate packets and the size and quantity of these is randomly produced by the nodes for more precise and realistic scenarios. As mentioned above, routing is performed through a modified version of flooding that neutralizes some links based on some rules. Finally, 250-650 nodes in multi-hop network were simulated.

A. Connectivity Model

Two nodes are connected in case that the distance between them is less than a certain value (threshold), otherwise they are not considered connected. Even though connection is established, packets might be potentially dropped due to fading characteristics, mobility and interference of the channels.

B. Random Direction Mobility Model

Mobility has two phases: moving or waiting. A node selects random direction to move and the move time is based on a constant distribution, which always returns the same value [41]. The speed of the node is returned by Gaussian distribution with mean and variance and the node waits for a certain time before start moving again. On the contrary, waiting time is returned by Poisson distribution.

C. Rayleigh Fading

Rayleigh fading is a statistical model for the effect of radio signal propagation [42] and considers the random variation of signal strength while it passes through transmission medium. It is best suited when there are many objects in the environment that scatter the signal with no dominant component. In case that there is such a dominant component, the Rician model is more suitable. The modelling of the probability density function takes the following form:

$$pR(r) = \frac{2r}{\Omega} e^{\frac{-r^2}{\Omega}}, r \geq 0 \tag{4}$$

where $\Omega = E(R^2)$ (5)

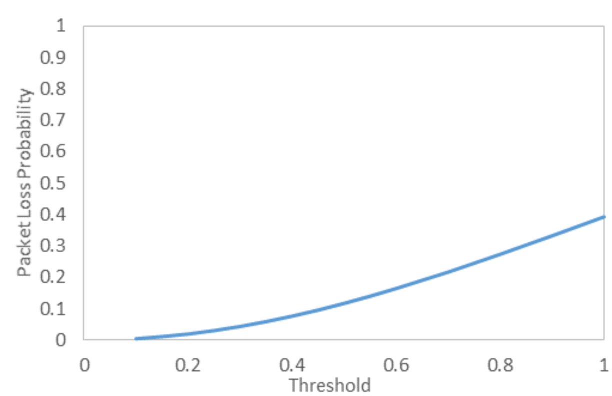

Fig. 2. Packet loss probability with scale = 1.

According to Rayleigh distribution, the probability of signal falling below some-point threshold is demonstrated in Fig. 2, whereas the average packet delivery ratio as a function of rounds is plotted in Fig. 3. Each node generates randomly a finite number of packets to send, choosing an arbitrary destination.

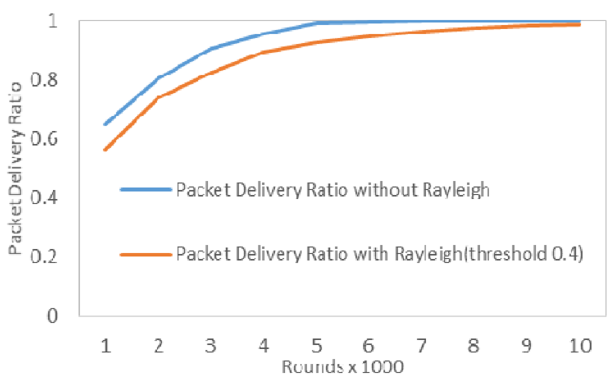

Fig. 3. Packets delivery ratio with Rayleigh fading. Threshold corresponds to signal level and packets are dropped in case that the signal level falls below 40% of the maximum signal strength during transmission.

V. Performance Evaluation Analysis, Experimental Results And Discussion

The parameters used when evaluating the network and protocol performance have a significant impact on the overall performance and QoS results. Throughout our simulations, the total successful packets received, the successful packets over dropped packets ratio, the average end-to-end delay and the Jitter (packet delay deviation) were considered as the most significant parameters. More specifically, all the 400 nodes are mobile with random velocities (*speed* = 3 with variance 0.5 simulation units) to random destinations according to the Random Direction Mobility model and a short pause (Poisson distribution *lambda* = 40) between consecutive movements in a 2000 x 1500 field area. Each station selects a random destination and keeps transmitting CBR traffic with random number of packets until all packets reach the destination. Retransmissions take place in case that the packets are dropped.

Based on the extensive simulation results, it is observed that the rate-adaptive bandwidth allocation scheme (RA-ALOHA) considerably overtakes the R-ALOHA (shown in Fig. 4). The total packets received are almost doubled using the proposed rate-adaptive bandwidth allocation scheme due to its effective bandwidth utilization based on the pessimistic way of channel condition estimation and the channel access restriction when observing weighted packets (total hops to destination). The results can be confirmed by the fact that the average delay per packet is minimized to half using the rate-adaptive bandwidth allocation scheme, as shown in Fig. 7. However, once the node's speed is increased, the outcome is almost similar as routing cannot cope effectively in such an environment.

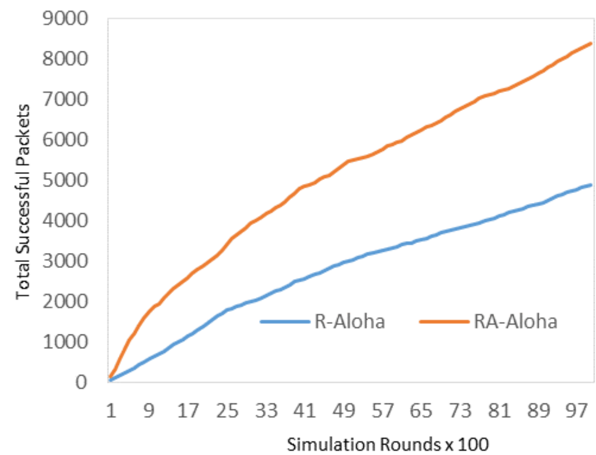

Fig. 4. Total successful packets over time.

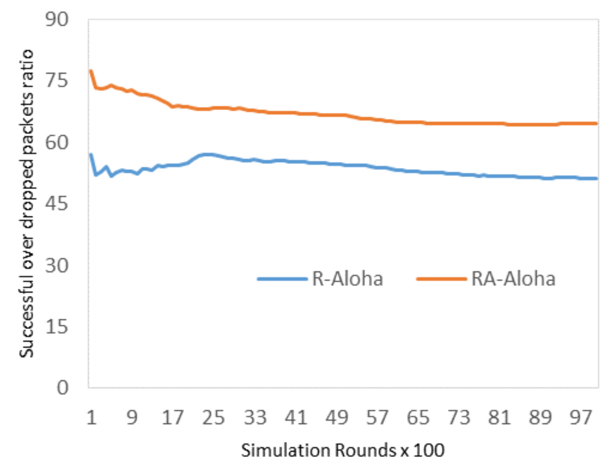

Fig. 5. Successful over dropped packets ratio with respect to the simulation rounds.

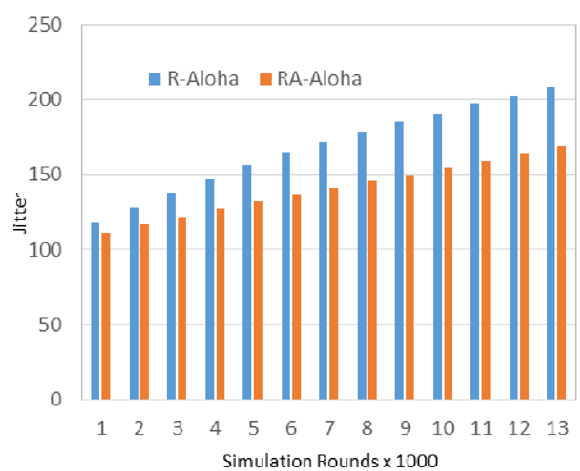

Figure 6. Jitter over time.

Fig. 5 indicates that the proposed rate-adaptive bandwidth allocation scheme has almost 20% better performance than R-ALOHA, when examining the successful over dropped packets ratio with respect to the simulation rounds (running time). Additionally, the proposed scheme outperforms standard R-ALOHA in terms of SDR (Successful Delivery Ratio) over time, as it experiences less dropped packets and delay (shown in Fig. 8). Finally, an extensive performance evaluation has been carried out aiming to investigate Jitter. The results indicate that the Jitter in the rate-adaptive bandwidth allocation scheme is significantly decreased due to the effective channel utilization (shown in Fig. 6).

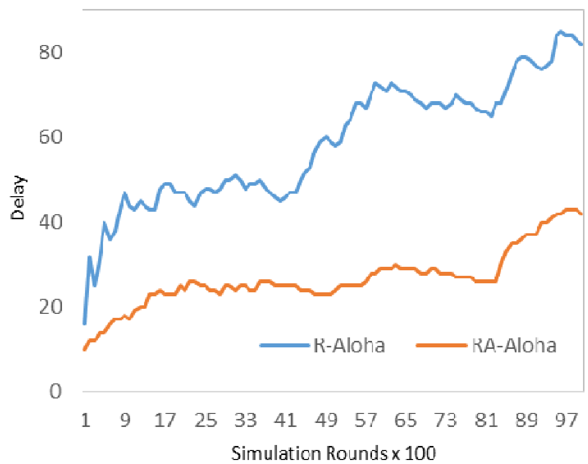

Fig. 7. Average packet delay.

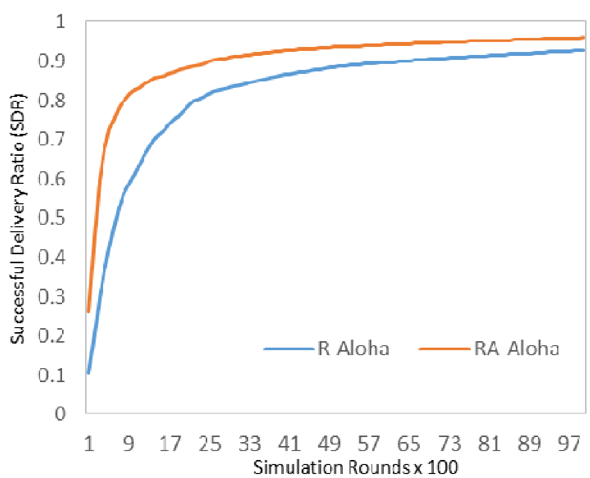

Fig. 8. Successful Delivery Ratio (SDR) over time.

VI. Conclusion

This paper elaborates on the performance evaluation of the proposed hybrid rate-adaptive MAC approach, based on the well-established ALOHA protocol, which is targeted to be applied in 5G mobile networks. The proposed rate-adaptive bandwidth allocation scheme utilizes the bandwidth of a channel effectively, improving the overall performance of the M2M communication, which is established in the 5G mobile environment. The simulation experiments were conducted in order to investigate the behavior of the proposed scheme and the results pointed out the significant improvement of the existing ALOHA-based schemes when implementing the rate-adaptive bandwidth allocation approach. The overall performance is considerably improved in terms of throughput and delay, whereas the SDR is kept at a relatively high level. From a QoS viewpoint, this mechanism is considered more suitable for M2M communications with low bandwidth transmissions, while the Jitter and the delay variation among transmissions are further reduced.

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