Delay Analysis of Wireless Broadband Networks with Non Real-Time Traffic

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Abstract. In this paper, we present the analysis of the mean overall packet delay of non real-time traffic in IEEE 802.16-based wireless broadband networks. We consider the case of contention-based bandwidth reservation. The system model accounts for both bandwidth reservation and packet transmission delay components of the overall delay. The queueing analysis is based on the description of the joint content of the outgoing subscriber station buffer and the base station grant buffer. This is achieved by means of a properly chosen bivariate embedded Markov chain. The mean overall packet delay is computed from its equilibrium solution. The analytical approach is verified by means of simulation. The corresponding analytical and simulation results show excellent agreement with each other.

Keywords: IEEE 802.16, queueing system, Markov chain, contention-based bandwidth reservation.

1 Introduction and Background

In wireless broadband networks, the users are distributed across a large geographic area and communicate via a base station (BS). As such, the BS is the coordinator of the network activity, which controls user communication in its vicinity. Recently, the proliferation of IEEE 802.16-based [1] broadband networks is observed. This is due to their relatively low cost, wide coverage and MAC mechanisms supporting a variety of quality of service (QoS) requirements.

The performance evaluation of IEEE 802.16 QoS features with bandwidth reservation is addressed by numerous research papers (see e.g. [2], [3], and [4]). The overall operation of the considered wireless broadband network is shown in Figure 1, in which both downlink (DL) and uplink (UL) transmissions are demonstrated. In the DL and the UL data packets are sent from the BS to its subscriber stations (SSs) and in the opposite direction, respectively. Initially, a SS issues a bandwidth request (BW-Req) in the UL (1UL), which is received by the BS (2UL). After processing these requests, the BS forms a transmission

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schedule and then forwards it to the SSs in the DL (1DL). Each SS receives the schedule (2DL) and transmits own data packets accordingly in the dedicated time-frequency slots (3UL, 4UL). If necessary, the BS may also transmit data packets to SSs in the DL (3DL, 4DL). As such, the overall system operation consists of bandwidth reservation and packet transmission functionalities, therefore the overall system model should account for both bandwidth reservation and packet transmission stages.

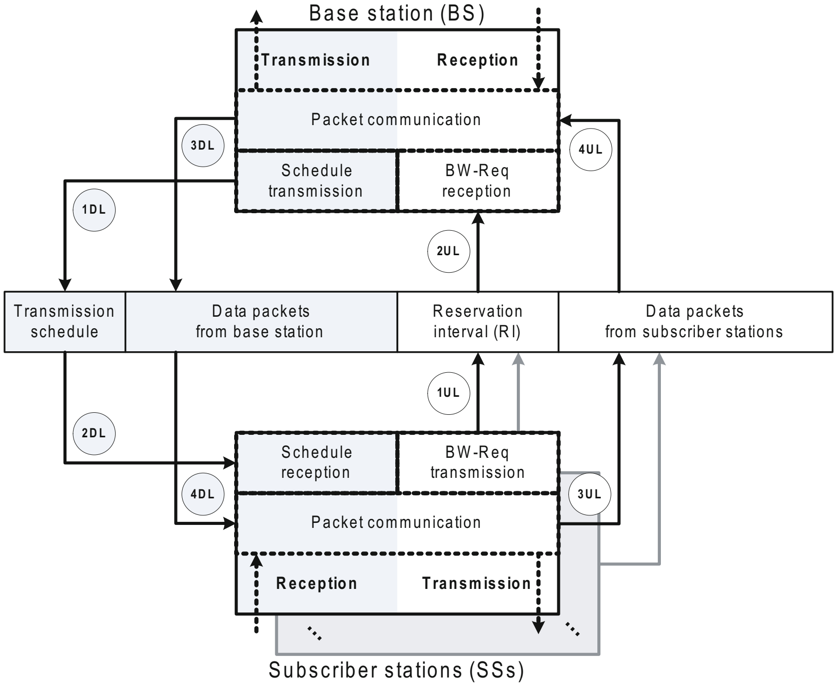

Fig. 1. System overall description

There has been little effort taken to address both aforementioned stages of the wireless broadband network functionality. This is due to the complexity of the overall system operation. The performance of IEEE 802.16 network was studied either by simulation [5], [6] or particular special cases were addressed analytically [7]. Moreover, in the majority of existing research papers the reservation and the transmission are considered separately. However, the operation of the real-world network (see Figure 1) includes both functionalities, which should be taken into account. In our previous work [8], we have studied the overall delay by addressing its both components and constructed a simple analytical upper bound on its mean value. In this paper, we continue our work and calculate the exact value of the mean overall delay.

2 System Model

In this section, we briefly outline the model of IEEE 802.16-based network, which is used to evaluate the delay at both reservation and scheduling stages. For more details, see our previous paper [8].

We consider the system that comprises a BS and N SSs, in which we focus only on the uplink transmissions. The delay analysis is conducted for non real-time (nrtPS) QoS profile. Only contention-based polling schemes are considered. Particularly, we concentrate on the broadcast polling.

The system operation time is divided into frames and T_f denotes the frame duration. The duration of a packet transmission is τ. At each SS, the packet arrival process is Poisson. The arrival rate is λ_i at SS i. Thus the overall arrival rate is $\lambda = \lambda_i N$. The duration of each contention-based transmission opportunity is ν. Moreover, the reservation interval (RI) of each frame comprises exactly K contention-based transmission opportunities.

A BW-Req is issued by the i-th SS whenever at least one new data packet arrives, of which the BS should be notified. The request contains the information about all the newly arrived packets since the last request sending. If a packet arrives to an empty outgoing buffer of SS i during the RI the SS must wait with sending the BW-Req for this packet until the next RI. We define $p_i^{(b)}$ as the probability of the successful BW-Req transmission at SS i, given that this SS takes part in the contention process (i.e. there is at least one new i-packet belonging to SS i in its outgoing buffer).

Additionally, below we introduce a set of assumptions to shape the system model.

Assumption 1. The probability of the successful BW-Req transmission at each SS in the RI of a frame, $p_i^{(b)}$, is assumed to be constant (see [8]).
Assumption 2. The BS maintains an individual grant buffer of infinite capacity for each SS.
Assumption 3. The grants in the individual BS grant buffer of each SS are processed in first-come-first-served order.
Assumption 4. Each SS can transmit exactly one packet in each UL sub-frame.
Assumption 5. For each SS, the feedback on the success/failure of its own BW-Req transmission, which is necessary for the collision resolution algorithm operation, is available.

The system is stable when for every SS on average the number of arriving packets does not exceed the number of departing packets, i.e.

$$\lambda_i < \frac{1}{T_f}, \quad i = 1, \ldots, N. \tag{1}$$

In general, our approach enables asymmetric traffic arrival patterns and different $p_i^{(b)}$ for the individual SSs. However, determining this probability for asymmetric system is more complicated. For the sake of simplicity, we consider only the symmetric model, i.e. at each SS the arrival rate of the uplink traffic is the same, λ_i. Similarly, $p_i^{(b)}$ is also the same for every SS.

3 Queueing Analysis

In this section, we detail a queueing model for the reservation and scheduling parts of the system. The statistical behavior of a SS is independent of that one for the other SSs, since each SS has an individual BS buffer and a separate data packet transmission period in the uplink sub-frame. Consequently, it is enough to model the behavior of the tagged SS separately from the rest of the system. Accordingly, we consider the system from the point of view of the tagged SS i.

We study the behavior of the tagged SS i at the embedded epochs, which are the end epochs of the first contention-based transmission opportunities in the RIs of the frames. In the queueing model, we assume that the BW-Req transmissions happen at the embedded epochs, i.e. in several cases somewhat earlier than in the real system, in which they happen at the end of the contention-based transmission opportunities. From the point of view of the queueing model, the "service start" of an i-packet is associated with an embedded epoch, in the frame preceding the one, in which that i-packet is transmitted. Such a "service start" of an i-packet is modeled by the event that the corresponding i-grant leaves the i-grant buffer of the BS, i.e. that i-grant is scheduled. The interval between the end epochs of the first contention-based transmission opportunities in the RIs in two consecutive frames is called a *cycle*.

By definition, the time instant of the successful BW-Req transmission from SS i is the *i-reservation event*. Similarly, by definition the instants of scheduling the BS grants in the BS grant buffer of SS i are the *i-scheduling events*. The positioning of the embedded epochs relatively to the corresponding *i-reservation* and *i-scheduling events* are shown in Figure 2.

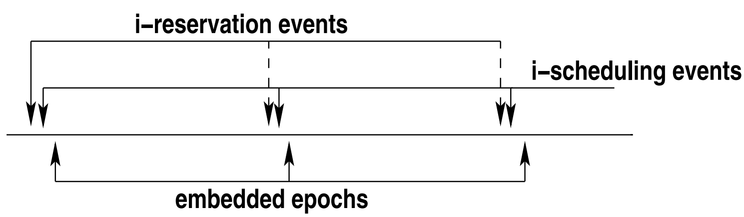

Fig. 2. Positions of the embedded epochs

The main assumption of the queueing analysis (see Assumption 1) is that the probability of the successful BW-Req transmission at SS i, given that this SS takes part in the contention process, $p_i^{(b)}$, is constant.

3.1 The Joint Content of the Outgoing and BS Grant Buffers of SS i at the Embedded Epochs

Let $q_i^{(r)}(\ell)$ be the number of i-packets in the outgoing buffer of SS i at the end of the first contention-based transmission opportunity in the RI in the ℓ-th frame for $\ell > 0$. Similarly, let $q_i^{(s)}(\ell)$ be the number of i-grants in the BS grant buffer of SS i at the end of the first contention-based transmission opportunity in the RI in the ℓ-th frame for $\ell > 0$. The sequence $\{(q_i^{(r)}(\ell), q_i^{(s)}(\ell)), \ell > 0\}$ is a bivariate homogeneous embedded Markov chain on the state space $(\{0,1,\ldots\},\{0,1,\ldots\})$. We say that the chain is in state (j,k) when $q_i^{(r)}(\ell) = j$ and $q_i^{(s)}(\ell) = k$. Let $p_i(j,k,n,m)$ denote the probability of transition from state j,k to state n,m in this Markov chain, i.e.

$$p_i(j,k,n,m) = P\{q_i^{(r)}(\ell+1) = n, q_i^{(s)}(\ell+1) = m \mid q_i^{(r)}(\ell) = j, q_i^{(s)}(\ell) = k\},$$
$$\ell \geq 1, \quad j,k,n,m \geq 0. \tag{2}$$

Let us consider the transitions from state (j,k) to state (n,m) in the above defined Markov chain. The transition from state $(0,0)$ to state $(0,0)$ happens either if there are no i-packet arrivals during the actual cycle or there is exactly one i-packet arrival during a cycle and the BW-Req transmission at the end of that cycle is successful, i.e. the newly generated i-grant is immediately scheduled to be sent. Thus the probability of this transition is given as

$$p_i(0,0,0,0) = e^{-\lambda_i T_f} + p_i^{(b)} \lambda_i T_f e^{-\lambda_i T_f}. \tag{3}$$

The transition from state $(0,0)$ to $(n,0)$ for $n \geq 1$ happens if there are n i-packet arrivals during a cycle and the BW-Req transmission at the end of that cycle is not successful. This leads to

$$p_i(0,0,n,0) = (1 - p_i^{(b)}) \frac{(\lambda_i T_f)^n}{n!} e^{-\lambda_i T_f}, \quad n \geq 1. \tag{4}$$

The transition from state $(0,k)$ to $(0,k-1)$ for $k \geq 1$ happens if there are no i-packet arrivals during the actual cycle. Thus we have

$$p_i(0,k,0,k-1) = e^{-\lambda_i T_f}, \quad k \geq 1. \tag{5}$$

The transition from state $(0,k)$ to $(0,k)$ for $k \geq 1$ happens if there is exactly one i-packet arrival during a cycle and the BW-Req transmission at the end of that cycle is successful, i.e. the newly generated i-grant is immediately scheduled to be sent. This results in

$$p_i(0,k,0,k) = p_i^{(b)} \lambda_i T_f e^{-\lambda_i T_f}, \quad k \geq 1. \tag{6}$$

The transition from state $(0,k)$ to $(0,m)$ for $k \geq 0$ and $m > k$ happens if there are exactly $m-k+1$ i-packet arrivals during a cycle and the BW-Req transmission at the end of that cycle is successful. The corresponding transition probability is given as

$$p_i(0,k,0,m) = p_i^{(b)} \frac{(\lambda_i T_f)^{m-k+1}}{(m-k+1)!} e^{-\lambda_i T_f}, \quad k \geq 0, \ m > k. \tag{7}$$

The transition from state $(0, k)$ to $(n, k-1)$ for $n \geq 1$ and $k \geq 1$ happens if there are exactly n i-packet arrivals during a cycle and the BW-Req transmission at the end of that cycle is not successful. This leads to

$$p_i(0, k, n, k-1) = (1 - p_i^{(b)}) \frac{(\lambda_i T_f)^n}{n!} e^{-\lambda_i T_f}, \quad n, k \geq 1. \tag{8}$$

The transition from state $(1, 0)$ to $(0, 0)$ happens if there are no i-packet arrivals during the actual cycle and the BW-Req transmission at the end of that cycle is successful. Thus it results in

$$p_i(1, 0, 0, 0) = p_i^{(b)} e^{-\lambda_i T_f}. \tag{9}$$

The transition from state $(j, 0)$ to $(n, 0)$ for $j \geq 1$ and $n \geq j$ happens if there are exactly $n - j$ i-packet arrivals during a cycle and the BW-Req transmission at the end of that cycle is not successful. The corresponding transition probability is given as

$$p_i(j, 0, n, 0) = (1 - p_i^{(b)}) \frac{(\lambda_i T_f)^{n-j}}{(n-j)!} e^{-\lambda_i T_f}, \quad j \geq 1, \ n \geq j. \tag{10}$$

The transition from state $(1, k)$ to $(0, m)$ for $k = 0$, $m \geq 1$ or $k \geq 1$, $m \geq k$ happens if there are exactly $m - k$ i-packet arrivals during a cycle and the BW-Req transmission at the end of that cycle is successful. This yields

$$p_i(1, k, 0, m) = p_i^{(b)} \frac{(\lambda_i T_f)^{m-k}}{(m-k)!} e^{-\lambda_i T_f}, \ \ k = 0, \ m \geq 1, \text{ or } k \geq 1, \ m \geq k. \tag{11}$$

The transition from state (j, k) to $(0, m)$ for $j \geq 2$, $k \geq 0$ and $m \geq k + j - 1$ happens if there are exactly $m - k - j + 1$ i-packet arrivals during a cycle and the BW-Req transmission at the end of that cycle is successful. This leads to

$$p_i(j, k, 0, m) = p_i^{(b)} \frac{(\lambda_i T_f)^{m-k-j+1}}{(m-k-j+1)!} e^{-\lambda_i T_f}, \ \ j \geq 2, \ k \geq 0, \ m \geq k + j - 1. \tag{12}$$

Finally the transition from state (j, k) to $(n, k - 1)$ for $j \geq 1$, $k \geq 1$ and $n \geq j$ happens if there are exactly $n - j$ i-packet arrivals during a cycle and the BW-Req transmission at the end of that cycle is not successful. The corresponding transition probability is given as

$$p_i(j, k, n, k-1) = (1 - p_i^{(b)}) \frac{(\lambda_i T_f)^{n-j}}{(n-j)!} e^{-\lambda_i T_f}, \ \ j \geq 1, \ k \geq 1, \ n \geq j. \tag{13}$$

Let $p_i^{(e)}(j, k)$ denote the equilibrium joint probability that the above Markov chain is in state j, k. To keep the computation of the joint probabilities tractable we apply an upper limit X_i both on the number of i-packets in the outgoing buffer of SS i and on the number of i-grants in the BS grant buffer of SS i, i.e. $j, k \leq X_i$. This results in finite number of equilibrium joint probabilities and transition probabilities and hence finite number of equilibrium equations. The proper value of X_i depends on the required precision and can be determined on iterative manner until the difference of consecutive values of probabilities $p_i^{(e)}(j,k)$, for every $j, k \leq X_i$, becomes less than the specified error. In the computation, the probabilities $p_i^{(e)}(j,k)$ for $j > X_i$ or $k > X_i$ are set 0, since they can be neglected.

Let $\mathbf{e}_j^{X_i+1} = (0,\ldots,0,1,0,\ldots,0)$ denote the $1 \times (X_i+1)$ vector with 1 at the j-th position. Additionally, let $\otimes$ stand for the Kronecker product. We define the $1 \times (X_i+1)^2$ vector $\boldsymbol{\theta}_i$ representing the equilibrium joint probabilities of the above Markov chain as

$$\boldsymbol{\theta}_i = \sum_{j=0}^{X_i} \sum_{k=0}^{X_i} p_i^{(e)}(j,k)\ \mathbf{e}_j^{X_i+1} \otimes \mathbf{e}_k^{X_i+1}. \tag{14}$$

We also define the $(X_i+1)^2 \times (X_i+1)^2$ matrix $\boldsymbol{\Pi}_i$ representing the transition probabilities of the embedded Markov chain as

$$\boldsymbol{\Pi}_i = \sum_{j=0}^{X_i} \sum_{k=0}^{X_i} \sum_{n=0}^{X_i} \sum_{m=0}^{X_i} p_i(j,k,n,m)\ \left(\mathbf{e}_j^{X_i+1} \otimes \mathbf{e}_k^{X_i+1}\right)^T \left(\mathbf{e}_n^{X_i+1} \otimes \mathbf{e}_m^{X_i+1}\right) \tag{15}$$

In the matrix $\boldsymbol{\Pi}_i$ the values of j, k and the values of n, m specify the row and the column indices of the corresponding transition probability $p_i(j,k,n,m)$.

The equilibrium joint probabilities of the embedded Markov chain can be uniquely determined from the following system of linear equations

$$\boldsymbol{\theta}_i \boldsymbol{\Pi}_i = \boldsymbol{\theta}_i, \quad \boldsymbol{\theta}_i \mathbf{e}^{(X_i+1)^2} = \sum_{j=0}^{X_i} \sum_{k=0}^{X_i} p_i^{(e)}(j,k) = 1, \tag{16}$$

where $\mathbf{e}^{(X_i+1)^2}$ denotes the $(X_i+1)^2 \times 1$ column vector having all elements equal to one.

The mean number of packets in the outgoing buffer of SS i at the end of the first contention-based transmission opportunity in the RI, $E[q_i^{(r)}]$, can be computed from the equilibrium joint distribution as

$$E[q_i^{(r)}] = \sum_{j=0}^{X_i} \sum_{k=0}^{X_i} j\ p_i^{(e)}(j,k). \tag{17}$$

Similarly, the mean number of i-grants in the BS grant buffer of SS i at the end of the first contention-based transmission opportunity in the RI, $E[q_i^{(s)}]$, can be computed also from the equilibrium joint distribution as

$$E[q_i^{(s)}] = \sum_{j=0}^{X_i} \sum_{k=0}^{X_i} k\ p_i^{(e)}(j,k). \tag{18}$$

3.2 The Mean of the Joint Content of the Outgoing and BS Grant Buffers of SS i At an Arbitrary Moment

Let q_i stand for the joint content of the outgoing and BS grant buffers of SS i at an arbitrary moment, i.e. the sum of the number of i-packets in the outgoing buffer of SS i and the number of i-grants in the BS grant buffer of SS i at an arbitrary moment.

The number of i-grants can change only just before the embedded observation epochs. This implies that the number of i-grants in the BS grant buffer of SS i at an arbitrary moment is the same as the one at the last embedded epoch.

The number of i-packets in the outgoing buffer of SS i at an arbitrary moment is the sum of the i-packets at the last embedded observation epoch and those, which arrive in the interval from the last embedded observation epoch to the arbitrary moment. This interval is the backward recurrence cycle time, whose mean length is $\frac{T_f}{2}$. Thus using (17) and (18), the mean number of i-packets in the outgoing buffer of SS i at an arbitrary moment can be expressed as

$$E[q_i] = \sum_{j=0}^{X_i}\sum_{k=0}^{X_i} j\ p_i^{(e)}(j,k) + \sum_{j=0}^{X_i}\sum_{k=0}^{X_i} k\ p_i^{(e)}(j,k) + \frac{\lambda_i T_f}{2}. \tag{19}$$

4 Overall Delay Analysis

4.1 The Components of the Overall Delay

We define the *overall delay* (W_i) of the tagged i-packet as the time interval spent from its arrival into the outgoing buffer of SS i up to the end of its successful transmission in the UL. We define also the *grant time of the tagged i-packet* as the time of the i-scheduling event of its i-grant, i.e. the end epoch of the first contention-based transmission opportunity in the RI in the frame preceding the one, in which the tagged i-packet is transmitted. The *overall delay* is composed of several parts:

$$W_i = W_i^r + \nu + W_i^s + W_i^t + \tau. \tag{20}$$

where the individual parts are defined as follows.

- W_i^r – reservation delay from the moment the i-packet arrives into the outgoing buffer of SS i to the start of the successful transmission of the corresponding BW-Req in the RI.
- ν – time of the successful BW-Req transmission, which equals the duration of the transmission opportunity.
- W_i^s – scheduling delay from the end of the successful BW-Req transmission of the tagged i-packet to its grant time.
- W_i^t – transmission delay from the grant time of the tagged i-packet to the start of its successful transmission in the next UL sub-frame
- τ – data packet transmission time.

4.2 Reservation and Scheduling Delays

The definition of the reservation delay implies that the reservation delay of the tagged i-packet is exactly the sojourn time of the tagged i-packet in the outgoing buffer of SS i. Similarly, it follows from the definition of the scheduling delay that it equals to the sojourn time of the i-grant assigned to the tagged i-packet in the BS grant buffer of SS i.

Consequently, the mean of the sum of the reservation and scheduling delays can be determined by applying Little's law on the mean number of joint content of the outgoing and BS grant buffers of SS i at an arbitrary moment. Using (19), this leads to

$$E\left[W_i^r + W_i^s\right] = \frac{1}{\lambda_i}\left(\sum_{j=0}^{X_i}\sum_{k=0}^{X_i} j\ p_i^{(e)}(j,k) + \sum_{j=0}^{X_i}\sum_{k=0}^{X_i} k\ p_i^{(e)}(j,k)\right) + \frac{T_f}{2}. \quad (21)$$

4.3 Transmission Delay

The transmission delay is a sum of the fixed time from the grant time of the tagged i-packet to the start of transmission of the i-packets in the next frame. Hence the mean transmission delay can be expressed as

$$E[W_i^t] = T_f + (K-1)\nu + (i-1)\tau. \quad (22)$$

4.4 Mean Overall Delay

Taking the mean of (20) and substituting the expressions (21) and (22), we obtain the expression of the mean overall delay as

$$E\left[W_i\right] = \frac{1}{\lambda_i}\left(\sum_{j=0}^{X_i}\sum_{k=0}^{X_i} j\ p_i^{(e)}(j,k) + \sum_{j=0}^{X_i}\sum_{k=0}^{X_i} k\ p_i^{(e)}(j,k)\right) + \frac{3T_f}{2} + i\tau + K\nu. \quad (23)$$

5 Numerical Results and Conclusion

In this section, we apply the derived analytical model to the performance evaluation of the uplink nrtPS packet service in the IEEE 802.16-2009 network [1] with contention-based reservation mechanism. We provide numerical examples to assess the performance of the IEEE 802.16 uplink nrtPS service flow evaluated with the considered analytical model. In order to generate performance data, a simulation program for IEEE 802.16-2009 MAC was developed. The program is an event-driven simulator that accounts for the discussed assumptions of the considered system model.

In our simulations, we set the default values recommended by WiMAX Forum [9] system evaluation methodology, which are also common values used in

Table 1. Basic evaluation parameters

Parameter	Value
PHY layer	OFDMA
Frame duration (T_f)	5 ms
Sub-channelization mode	PUSC
DL/UL ratio	2 : 1
Channel bandwidth	10 MHz
MCS	16 QAM $^3/_4$
Packet length	160 bytes
Number of SSs (N)	15
Total capacity per frame for all SSs	15 packets

practice [10] (see Table 1). We assume a 10 MHz TDD system with 5 ms frame duration, PUSC sub-channelization mode and a DL : UL ratio of 2 : 1. In the numerical examples we use normalized arrival flow rate, in which the critical arrival rate that saturates the system is 1.

According to [11], the UL sub-frame comprises 175 slots. Assuming MCS of 16 QAM $^3/_4$, the IEEE 802.16-2009 system transmits 16 bytes per UL slot. We consider fixed packet length of 1600 bytes (10 slots) for all service flows, which results in capacity for sending 15 packets per UL sub-frame. The remaining 25 UL slots represent the necessary control overhead including exactly 1 contention-based transmission opportunity per RI to minimize the overhead (i.e. $K = 1$).

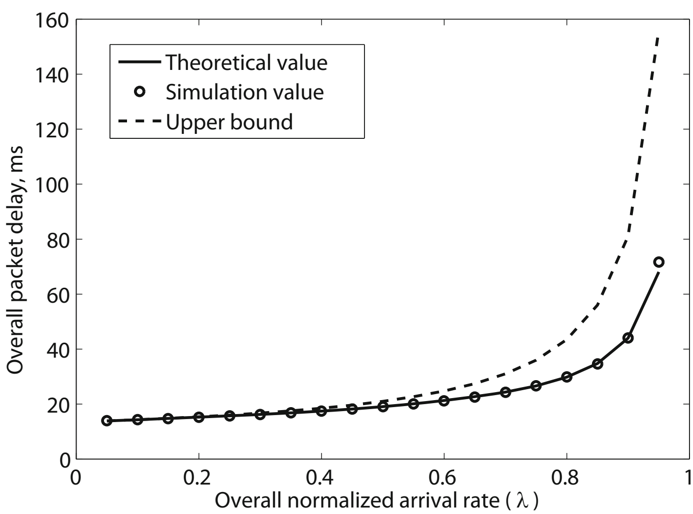

Fig. 3. Numerical results: overall delay vs. arrival rate

The determination of the probability of the successful BW-Req transmission $p_i^{(b)}$ for symmetric system can be found in our previous work [8].

In Figure 3 and Figure 4, we compare analytical and simulation results for the mean overall packet delay. In particular, in Figure 3 and in Figure 4 the dependency of the mean delay on the overall normalized arrival rate at fixed

$p_i^{(b)} = 0.5$ and on $p_i^{(b)}$ at fixed normalized $\lambda = 0.5$ can be seen, respectively. The presented analytical approach to the overall mean packet delay computation demonstrates excellent agreement with simulation data. Moreover, we also plot the closed-form analytical upper bound from [8] to conclude that the currently proposed analysis is much more precise in predicting the mean delay values.

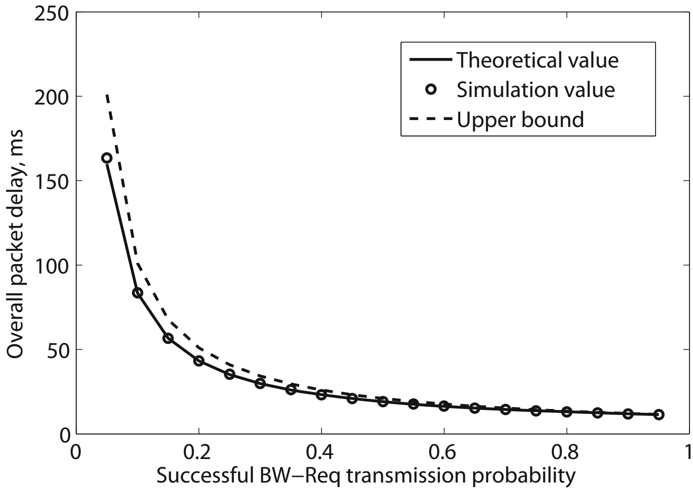

Fig. 4. Numerical results: overall delay vs. contention success probability

6 Final Remarks

It is our future work to use a public simulator to further verify the presented analytical approach also under real-world settings.

Furthermore, we notice that a potential perspective to continue this work is to investigate the determination of the probability of the successful BW-Req transmission $p_i^{(b)}$ also for the asymmetric system. It would enable the relaxation of the assumption on symmetric uplink traffic used in the numerical evaluation.

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