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Modeling Slotted Aloha of WBAN in Non-Saturated Conditions

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Abstract

The IEEE 802.15.6 is a communication standard for Wireless Body Area Networks (WBANs). This standard includes a prioritized slotted Aloha as a choice for medium access control. This protocol is different from the traditional version as it has integral considerations for certain priorities of users. It attempts to resolve collision by halving the probability of retransmission, lower bounded by to a minimum, in the alternate slots to follow. In this paper, we present an analytical model to compute the non-saturated throughput of this protocol in the presence of finite number of nodes. The model is validated against simulation.

Keywords: IEEE 802.15.6, WBAN, Throughput; Non-saturation, Slotted Aloha

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1. Introduction

Wireless Body Area Network (WBAN) is a network of tiny wireless medical sensors which may be attached to the body surface or implanted into the tissues. These medical sensors are capable of measuring significant physiological parameters like heartbeat, blood pressure, body and skin temperature, oxygen saturation, respiration rate, electrocardiograms, and other parameters. A WBAN has shown to be adequate for sending patient's information to a remote server or physician to maintain optimum health status. This technology is expected to reduce the amount of time doctors require to identify the problem, the amount of paper work required and eliminates the duplication of patient records [1]. This technology can be exploited also in many other fields, including fitness monitoring, gaming, military services, and wearable computing etc. An abstract view of medical WBAN is shown in **Fig. 1**.

The currently available standards such as IEEE 802.11, IEEE 802.11e, IEEE 802.15.4, and IEEE 802.15.3 are not appropriate for WBAN since they do not support the combination of reliability, low power, high data rate, and QoS. Therefore, to fulfill the requirements of WBAN, the IEEE 802.15 Working Group formed Task Group 6 (TG6) in November 2007 to develop a communication standard optimized for low-power and short-range in-body/on-body nodes to serve a variety of medical, consumer electronics and entertainment applications. The IEEE 802.15.6 standard settled in 2012 [2] calls attention to the importance of the emergence of WBAN.

All the nodes and the hubs in the network are structured into logical sets, referred to as Body Area Networks (BANs) and coordinated by their respective hubs for medium access and power management. In every BAN there is a hub whereas the number of nodes in a BAN may range from 0 to 64. There are 8 different access categories which indicate the user priorities for accessing the medium.

WBAN employs either Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) or slotted Aloha to access the medium. Ultra-Wide Band physical layer (UWB PHY) employs slotted Aloha as medium access protocol. The UWB PHY specification is designed to offer robust performance for WBANs and to provide safe power levels for the human body and low interference to other devices.

A particular variety of slotted Aloha is adopted in IEEE 802.15.6 standard. This is different from the traditional one in the sense that it is designed to deal with rather limited number of users attempting to resolve contention through reduction of the retransmission probability in a distinct way.

In this paper, we focus on the performance evaluation of slotted aloha scheme proposed in IEEE 802.15.6 in the assumption of ideal channel conditions and finite number of nodes. We develop a markov chain based analytic model in non-saturated conditions.

The paper is outlined as follows. After a brief review of related work in section 2, the slotted aloha of WBAN is reviewed in section 3. The Markov model is introduced and solved in section 4. The section 5 validates the model by comparing the analytical results with that obtained by simulation. Concluding remarks are in section 6.

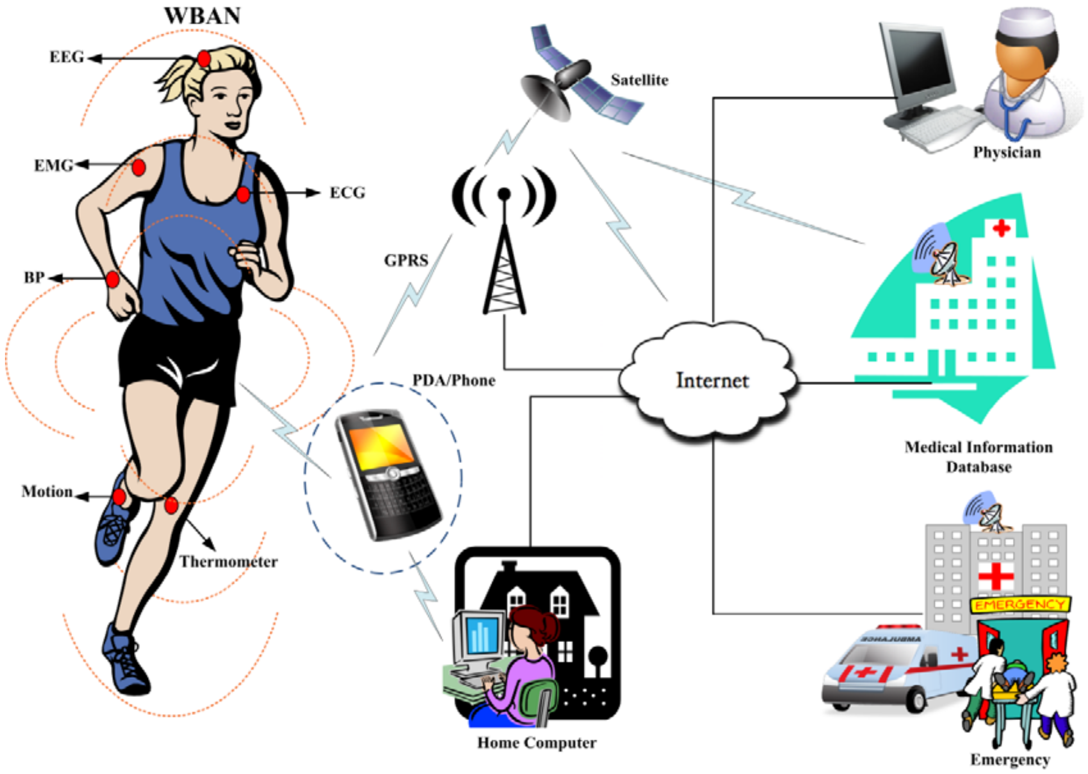

Fig. 1. Abstract view of WBAN [1]

2. Related Works

Very few studies reported in the literature to analyze the random access mechanism of IEEE 802.15.6 MAC. However, with regards to the MAC protocols for WBAN, various studies exist such as [3][4][5][6][7][8][9]. Analysis of the CSMA/CA protocol can be found in many papers based on various standards such as IEEE 802.11 [10][11][12][13] and IEEE 802.15.4 [14][15][16]. The CSMA/CA of IEEE 802.15.6 have been analyzed in [17][18][19].

The seminal paper [10] found the saturation throughput of IEEE 802.11 distributed coordination function. In saturated condition, it is assumed that each node always has a packet waiting to be transmitted. Our paper in [20] presented the saturation throughput analysis of 802.15.6 slotted Aloha. But networks do not typically operate in saturated conditions. In this paper, we extend our saturated model for a non-saturated one. We assume that nodes do not know the number of transmitting nodes a particular slot a priori, and know only whether or not their transmission succeeded after the fact.

The Aloha protocol [21] is a fully decentralized medium access protocol that does not perform carrier sensing. The subsequent slotted Aloha protocol [22] was introduced to improve utilization of the shared medium by synchronizing the transmission of the devices in within time slots. However, IEEE 802.15.6 incorporated some unique features in slotted aloha which are different from the traditional one. In this work, we focus on the performance of stable slotted aloha for the WBAN, where only finite numbers of users access the medium simultaneously. An analysis of generalized slotted-Aloha protocols can be found in [23]. Recent work using Game Theory to analyze the Aloha protocol can be found in [24][25].

3. WBAN and Slotted Aloha Access

The UWB PHY specification is designed to offer robust performance for WBANs and to deliver a large scope for implementation opportunities for high performance, robustness, low complexity, and ultra low power operation. This PHY employs slotted Aloha as medium access protocol which is described in this section.

The IEEE 802.15.6 standard defines eight user priorities, $UP_i, i = 0, \dots, 7$. These users are differentiated by the maximum and minimum contention probability (CP) as shown in **Table 1**.

Table 1. Contention probability (CP) thresholds for slotted aloha access

User Priority (UP)	**Traffic Designation**	**CP$_{max}$**	**CP$_{min}$**
0	Background (BK)	$\frac{1}{8}$	$\frac{1}{16}$
1	Best effort (BE)	$\frac{1}{8}$	$\frac{3}{32}$
2	Excellent effort (EE)	$\frac{1}{4}$	$\frac{3}{32}$
3	Video (VI)	$\frac{1}{4}$	$\frac{1}{8}$
4	Voice (VO)	$\frac{3}{8}$	$\frac{1}{8}$
5	Media data of network control	$\frac{3}{8}$	$\frac{3}{16}$
6	High priority medical data or network	$\frac{1}{2}$	$\frac{3}{16}$
7	Emergency or medical event report	1	$\frac{1}{4}$

To obtain a new contended allocation for the transmission or retransmission of a packet a node shall set its CP as follows.

1. If the node did not obtain any contended allocation previously, it shall set the CP to $\mathrm{CP}_{\mathrm{max}}[UP]$. If the node succeeded, it shall set the CP to $\mathrm{CP}_{\mathrm{max}}[UP]$.
2. If the node failed in the last contended allocation it had obtained,
    a) It shall keep the CP unchanged if this was the m-th time the node had failed consecutively, where m is an odd number;

    b) It shall halve the CP if this was the n-th time the node had failed consecutively, where n is an even number.

    c) If halving the CP would make the new CP smaller than $CP_{min}[UP]$, the node shall set the CP to $CP_{min}[UP]$.

The CP value is not changed when it gets the value of CP_{min} at the m-th retry. The value of m can be found as

$$m = 2\left\lceil \log_2\left(\frac{\mathrm{CP_{max}}}{\mathrm{CP_{min}}}\right)\right\rceil \tag{1}$$

The node shall have obtained a contended allocation delimited by the current aloha slot if $z \leq CP$ or shall not have otherwise, where z is a value the node has newly drawn at random from the interval $[0, 1]$. It may be noted that each Aloha slot is of equal length.

4. Markov Model for WBAN Slotted Aloha

An analytical model for slotted Aloha in WBAN is presented in this section for non-saturated case. A single-hop wireless network consisting of N nodes are considered. It is assumed that all the nodes in the network have same payload size.

The Discrete Time Markov Chain (DTMC) as shown in **Fig. 2** is modeled after the states that a node can be in while attempting to transmit the packets. The decreasing probability of transmission and the division of the time into sequence of well-defined slots as stated in the standard are keys to the formulation of the model. $\{l, 0,1,2, \dots, \mathrm{m}\}$ are the states of a node. For the tagged node, that happens to be in state k, event probabilities are denoted as:

$\mathrm{p}(\mathrm{k}, l)$: remains idle in the current slot without attempting to transmit

$\mathrm{p}(\mathrm{k}, \mathrm{s})$: transmits successfully in the current slot

$\mathrm{p}(\mathrm{k}, \mathrm{c})$: transmits in the current slot that ends up in collision

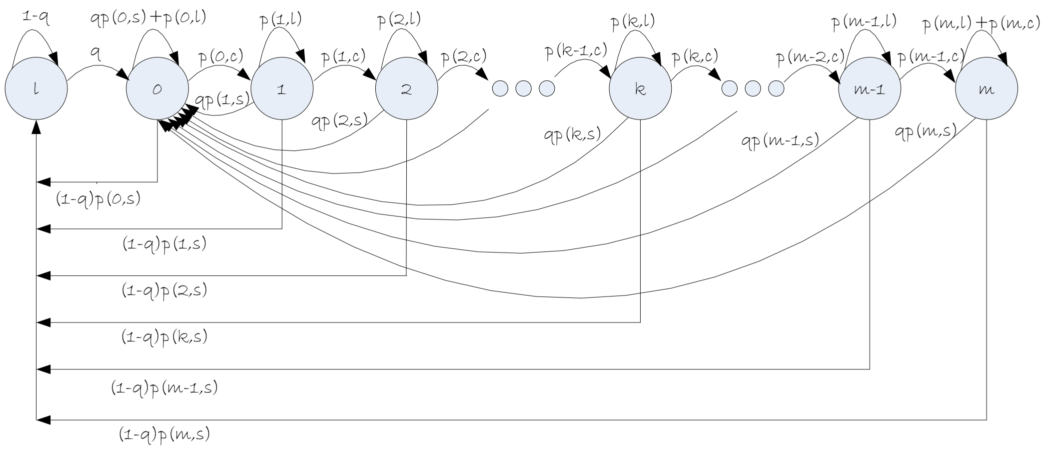

Fig. 2. Discrete time Markov chain for the nodes

Other per node quantities are:

l: the idle state when a given node does not have a packet to contend with.

q: If packets arrive at the MAC in a Poisson manner with rate λ (per node), then the probability of no arrivals in a slot is $\mathrm{e}^{-\lambda}$. Thus, the probability that a packet is available by the tagged node in the given slot is $\mathrm{q} = 1 - \mathrm{e}^{-\lambda}$. Consequently, the probability that there is no packet available is $1 - \mathrm{q}$.

The one-step transition probabilities of the DTMC are:

$$\begin{cases} P(0|0) & = q.p(0,s) + p(0,l) & \\ P(k+1|k) & = p(k,c), & 0 \leq k \leq m-1 \\ P(0|k) & = q.p(k,s), & 1 \leq k \leq m \\ P(k|k) & = p(k,l), & 1 \leq k \leq m-1 \\ P(m|m) & = p(m,c) + p(m,l) & \\ P(l|l) & = 1-q & \\ P(l|k) & = (1-q).p(k,s), & 0 \leq k \leq m \\ P(0|l) & = q & \end{cases} \tag{2}$$

The equation (2) depicts following cases:

The first case is for state 0 where either another packet transmits after a successful transmission or remains idle in the current slot without attempting to transmit. Upon an unsuccessful transmission, the node moves to state $(k+1)$ to obtain a new contended allocation for the retransmission as shown in the second transition. The third case shows that after a successful transmission the node has packet to transmit and hence enters at the state 0. The node remains idle in the current slot without attempting to transmit which is shown in fourth case. The fifth equation reflects an idle or failure event when it reaches to the state m. The transition probability $P(l|l)$ shows a node remains in the idle state as it has no packet to transmit. The seventh case depicts that after a successful transmission the node has no packet to transmit, and hence enters the idle state. The last case expresses that a new packet has arrived for transmission.

We select one tagged node from a user class and analyze according to our proposed model. Let α be the probability that the tagged node transmits in a generic slot regardless of the fate of that transmission.

The standard specifies that at alternative number of attempts with the same packet, the probability of transmission is halved. If the first transmission attempt is made for a given packet with the base probability(CP_{max}), attempt in state k is made with probability

$$1 - p(k,l) = \max\left(\frac{CP_{max}}{2^{[k/2]}}, CP_{min}\right) \tag{3}$$

The collision probablity β, is the probablity that the tagged node encounters a collision in a time slot if at least one of the remaining $(N-1)$ nodes transmits, which can be expressed as

$$\beta = 1 - (1-\alpha)^{N-1} \tag{4}$$

Success of a transmission or collision by the tagged node in an arbitrary slot depends on the activities of the rest of the $(N-1)$ nodes in that slot; this yields the probabilites of successful and collided transmission as follow respectively

$$p(k,s) = (1-\beta).\{1 - p(k,l)\} \tag{5}$$

$$p(k,c) = \beta.\{1 - p(k,l)\} \tag{6}$$

With stationary state probabilities represented by π_k $(k = l, 0,1,2,\ldots,m)$, the balance equations are, as depicted in the **Fig. 2**, given by

$$\mathrm{\pi}_l = \mathrm{\pi}_l.(1-\mathrm{q}) + \sum_{\mathrm{k}=0}^{\mathrm{m}} \mathrm{\pi}_\mathrm{k}.(1-\mathrm{q}).\mathrm{p}(\mathrm{k},\mathrm{s}) \tag{7}$$

$$= \frac{1-\mathrm{q}}{\mathrm{q}}.\sum_{\mathrm{k}=0}^{\mathrm{m}} \mathrm{\pi}_\mathrm{k}.\mathrm{p}(\mathrm{k},\mathrm{s})\} \tag{8}$$

$$\mathrm{\pi}_0 = \mathrm{\pi}_l.\mathrm{q} + \mathrm{\pi}_0.\{\mathrm{q}.\mathrm{p}(0,\mathrm{s}) + \mathrm{p}(0,l)\} + \sum_{\mathrm{k}=1}^{\mathrm{m}} \mathrm{\pi}_\mathrm{k}.\mathrm{q}.\mathrm{p}(\mathrm{k},\mathrm{s}) \tag{9}$$

$$= \frac{\mathrm{q}}{1-\mathrm{p}(0,l)}.\{\mathrm{\pi}_l + \sum_{\mathrm{k}=0}^{\mathrm{m}} \mathrm{\pi}_\mathrm{k}.\mathrm{p}(\mathrm{k},\mathrm{s})\} \tag{10}$$

$$\mathrm{\pi}_\mathrm{k} = \mathrm{\pi}_{\mathrm{k}-1}.\mathrm{p}(\mathrm{k}-1,\mathrm{c}) + \mathrm{\pi}_\mathrm{k}.\mathrm{p}(\mathrm{k},l),(1 \le \mathrm{k} \le \mathrm{m}-1) \tag{11}$$

$$= \mathrm{\pi}_{\mathrm{k}-1}.\frac{\mathrm{p}(\mathrm{k}-1,\mathrm{c})}{1-\mathrm{p}(\mathrm{k},l)} \tag{12}$$

$$\mathrm{\pi}_\mathrm{m} = \mathrm{\pi}_{\mathrm{m}-1}.\mathrm{p}(\mathrm{m}-1,\mathrm{c}) + \mathrm{\pi}_\mathrm{m}.\{\mathrm{p}(\mathrm{m},l) + \mathrm{p}(\mathrm{m},\mathrm{c})\} \tag{13}$$

$$= \mathrm{\pi}_{\mathrm{m}-1}.\frac{\mathrm{p}(\mathrm{m}-1,\mathrm{c})}{\mathrm{p}(\mathrm{m},\mathrm{s})} \tag{14}$$

The normalization relation is

$$\mathrm{\pi}_l + \sum_{\mathrm{k}=0}^{\mathrm{m}} \mathrm{\pi}_\mathrm{k} = 1 \tag{15}$$

Rearranging (8) and writing in term of $\mathrm{\pi}_0$

$$\mathrm{\pi}_l = \frac{1-\mathrm{q}}{\mathrm{q}}.\{\mathrm{\pi}_0.\mathrm{p}(0,\mathrm{s}) + \sum_{\mathrm{k}=1}^{\mathrm{m}-1} \mathrm{\pi}_\mathrm{k}.\mathrm{p}(\mathrm{k},\mathrm{s}) + \mathrm{\pi}_\mathrm{m}.\mathrm{p}(\mathrm{m},\mathrm{s})\} \tag{16}$$

$$= \frac{1-\mathrm{q}}{\mathrm{q}}.\mathrm{\pi}_0.\mathrm{CP}_{\mathrm{max}}.\{(1-\mathrm{\beta}) + (1-\mathrm{\beta}).\sum_{\mathrm{k}=1}^{\mathrm{m}-1} \mathrm{\beta}^\mathrm{k} + \mathrm{\beta}^\mathrm{m}\} \tag{17}$$

Similarly, writing (12) and (14) in term of $\mathrm{\pi}_0$ as follows

$$\pi_k = \frac{\pi_0.\mathrm{\beta}^k.CP_{max}}{1-p(k,l)},(1 \le k \le m-1) \tag{18}$$

$$\pi_m = \frac{\pi_0 . \beta^m . CP_{max}}{(1-\beta).\{1-p(m,l)\}} \tag{19}$$

Putting π_l, π_k and π_m from above equations in (15) produces

$$\pi_0 = \frac{1}{\frac{1-q}{q}.\mathrm{CP}_{max}.\left\{(1-\beta)+(1-\beta).\sum_{k=1}^{m-1}\beta^k+\beta^m\right\} + \sum_{x=0}^{\frac{m}{2}-1}(2^x.\beta^{2x}+2^x.\beta^{2x+1}) + \frac{2^{\frac{m}{2}}.\beta^m}{1-\beta}} \tag{20}$$

The main quantity of interest is α and it can be expressed as

$$\alpha = \sum_{k=0}^{m} \pi_k\{1-p(k,l)\} \tag{21}$$

$$= \pi_0.\left(\frac{1}{1-\beta}\right).\mathrm{CP}_{max} \tag{22}$$

Finally, after some algebra, (22) gives

$$\alpha = \frac{\mathrm{CP}_{max}.(1-2\beta^2)}{\frac{1-q}{q}.\mathrm{CP}_{max}.(1-2\beta^2)(1-\beta)\left\{(1-\beta)+(1-\beta).\sum_{k=1}^{m-1}\beta^k+\beta^m\right\} + (1-\beta^2).\{1-(\sqrt{2}\beta)^m\} + (1-2\beta^2).2^{\frac{m}{2}}.\beta^m} \tag{23}$$

Equations (4) and (23) form a nonlinear system with two unknowns β and α which can be solved using numerical techniques. Then these can be used to estimate the desired performance metrics such as throughput. The normalized system throughput is:

$$\eta = N\alpha\,(1-\alpha)^{N-1} \tag{24}$$

5. Model Validation

The pair of non-linear simultaneous equations (4) and (23) are solved for fixed point using MATLAB. A custom made simulator using C++ programming language is used to validate the model. We took the parameters of the default mode that employs impulse UWB (IR-UWB) as stated in the standard.

We consider a homogeneous group of nodes where all the nodes are of same user priority, i.e. all of the nodes have same CP_{max}, CP_{min} and other relevant parameters. We show the results for UP_0, UP_3 and UP_5. The analytical results coincide with the simulations results.

Fig. 3 shows the normalized non-saturated system throughput for UP_0 given by Equation (24) as a function of λ for three different network sizes where *N* is equal to 10, 20 and 30. It can be observed that the throughput increases up to a certain point as λ increases and the throughput starts decreasing and saturated after that point. The throughput drastically decreases for larger N and slowly decreases for the smaller N before the saturation point. The throughput for larger network size increases more sharply than for smaller netwrok size. Generally, the peak throughput occur prior to saturation which are reflected in the cases when the values of N are equal to 20 and 30.

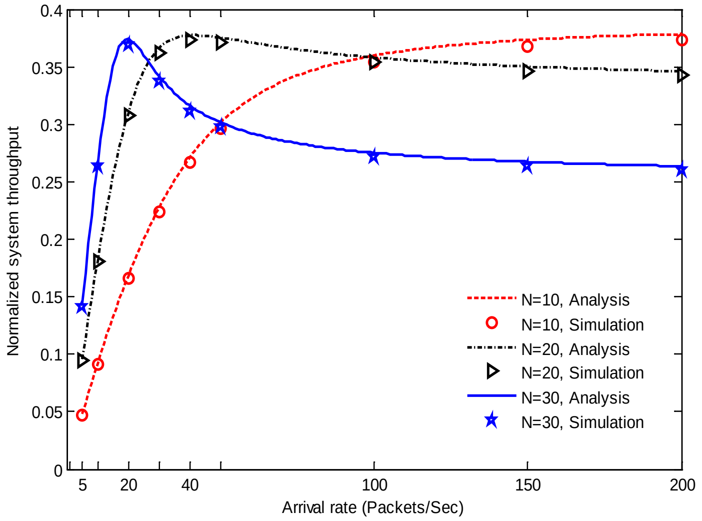

Fig. 3. Non-saturated system throughput of UP_0 for different network sizes

Fig. 4 shows the normalized non-saturated system throughput for three different user priorities; UP_0, UP_3 and UP_5. The network size is kept fixed at N is equal to 5 to compare throughput among these users. The higher user priorities show higher throughput as it has greater $\mathrm{CP}_{\mathrm{max}}$ and $\mathrm{CP}_{\mathrm{min}}$ as compare to the lower priority users. The throughput are almost same for all these users when arrival rates are below 20 packets/sec. It means that the higher priority users give higher throughput for higher arrival rates.

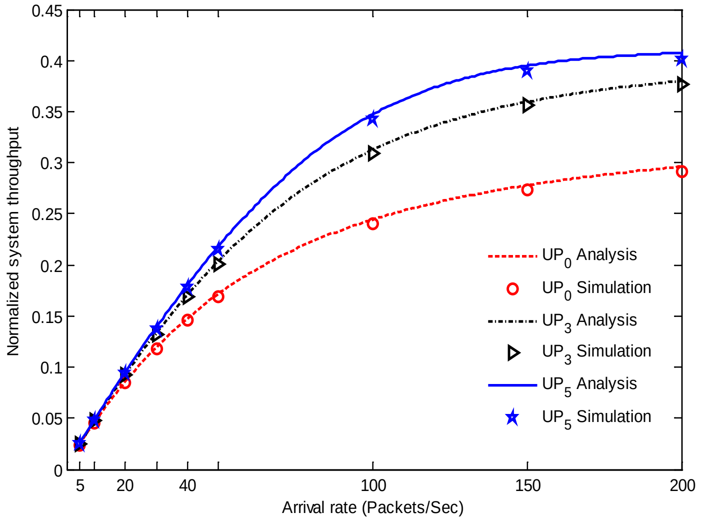

Fig. 4. Non-saturated system throughput of UP_0, UP_3 and UP_5 $[N = 5]$

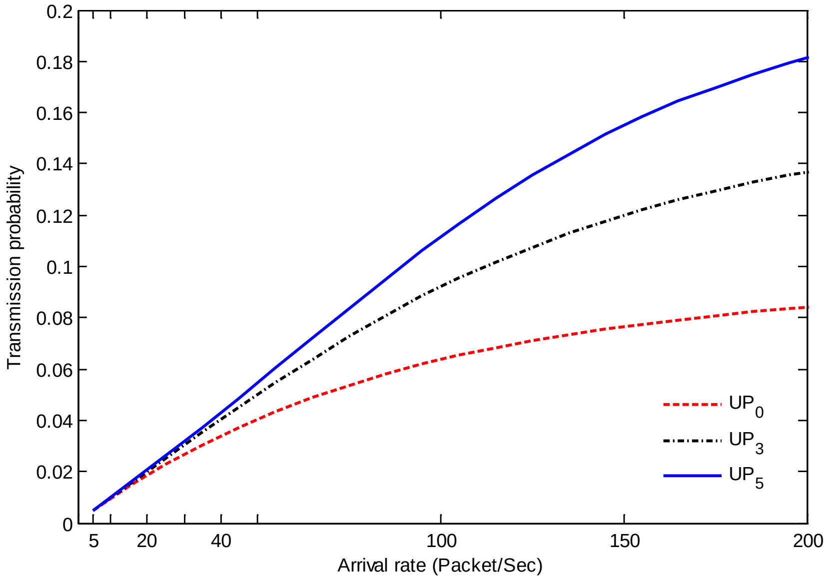

Fig. 5. Transmission probabilities $[N = 5]$

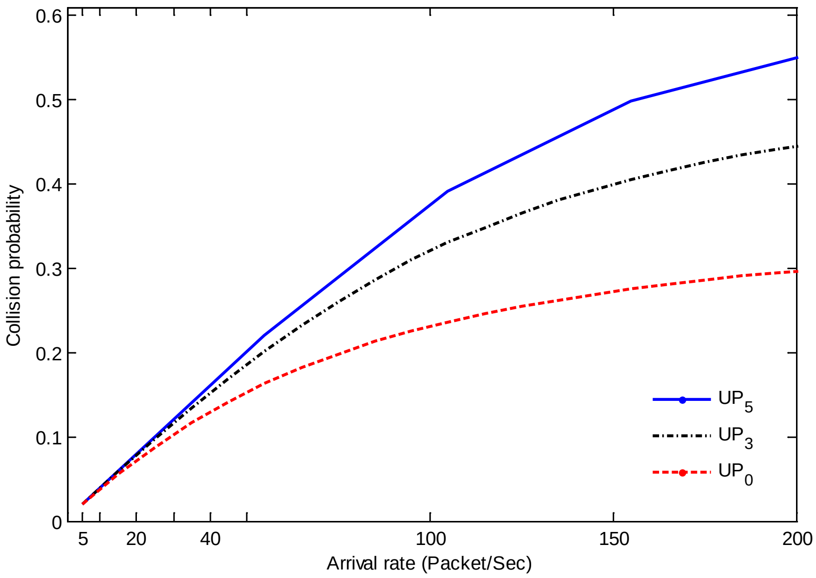

Fig. 6. Collision probabilities $[N = 5]$

Fig. 5 and **Fig. 6** show the transmission and collision probabilities for these three users respectively. The network size is taken 5 for comparison. As expected, the transmission probabilities are higher for higher user priorities. In both figures, the gap of transmission and collision probabilities increases between the higher and the lower priority users as λ increases.

However, the difference are lower for the lower arrival rates. These probabilities explain the trends of throughput curves of different users in **Fig. 4**.

It can be observed that the throughput strongly depends on system parameters, mainly network size, $\mathrm{CP}_{\max}$ and $\mathrm{CP}_{\min}$. We have shown only three users to show the results. However, any other user priority classes can be easily incorporated in our model.

5. Conclusion

We have proposed an analytical model to compute the throughput of slotted Aloha protocol for WBAN in non-saturated conditions for different user priority classes. The simulation results validate the analytical results. The analytical model presented in this paper can be employed to quantitatively determine the protocol parameters in certain application scenarios. The model is simple and can be extended for related protocol variants and for the heterogeneous users.

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