PAPER

Efficient Resource Utilization for Heterogeneous Wireless Personal Area Networks

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SUMMARY Wireless personal area networks (WPANs) will play an important role in next-generation communication networks. Currently, two technologies are being considered for the physical layer of WPANs, based on the two ultra wideband (UWB) standards, namely, multiband orthogonal frequency division multiplexing (MB-OFDM) UWB and direct-sequence (DS) UWB. The coexistence issue of these two types of WPANs in the same coverage area, raises new issues and introduces new problems which should be dealt with to avoid performance degradation. In particular, efficient radio resource management (RRM) in such environments is challenging. Indeed, the coexistence of heterogenous UWB based WPANs (UPANs) has an ad hoc nature, which requires RRM approaches that are different from traditional infrastructure-based ones. In this paper, we propose new algorithms for two RRM modules in heterogeneous UPANs, namely, radio access technology (RAT) selection and vertical handoff (VHO). To improve the overall performance of the system, our design considers possible narrowband interference (NBI) in the environment as well as the link outage probability, in the decision process. We also provide an analytical model based on a 4D Markov process to study the system in equilibrium and derive the performance metrics, namely, the new-call and handoff-call blocking probabilities, throughput and average carried traffic. Numerical results and comparisons show that our design achieves enhanced performance in terms of throughput and grade of service (GoS).
key words: *radio resource management, heterogeneous networks, MB-OFDM, DS-UWB, vertical handoff, grade of service*

1. Introduction

Wireless personal area networks (WPANs) are an important part of the future vision of seamless communications. WPANs provide short-range ad hoc wireless connectivity. Currently, there are two ultra wideband (UWB)-based proposals for the physical layer in WPANs: multiband orthogonal frequency division multiplexing (MB-OFDM) [1] and direct-sequence (DS) UWB [2]. In these networks, radio resource management (RRM) will play a major role in the proper assignment of resources and reducing interference. RRM consists of several modules, e.g., call admission control [3], radio access technology (RAT) selection, vertical handoff (VHO) [4]–[6], power control, etc. RRM becomes especially complicated in the case of heterogeneous UWB based WPANs (UPANs), where two different technologies need to coexist in the same coverage area. Most studies on RRM in heterogeneous networks, consider the problem from a general perspective and most assume the conventional microcell-macrocell scenario where the networks have different and partially overlapping coverage. To the best of our knowledge, there have been no research results on the RRM in heterogeneous WPANs, particularly when the PHY layer has different UWB technologies.

Surveying the previous studies that are most related to our topic, it is worth mentioning [7], [8] and [9]. In [7], an analytical model that considers different classes of calls was proposed for handoff management in cellular networks. In fact, the authors considered a priority handoff algorithm based on channel reservation for real-time and non-real-time services in homogeneous cellular networks. The research work in [8] discussed VHO in fourth-generation heterogeneous networks, by considering different parameters for the VHO policy design such as service type, costs and user conditions. In [9], Markov chain is used to model the RAT selection problem for a heterogeneous network consisting of TDMA and wideband CDMA networks. Four different RAT selection policies are studied in this model. This work does not consider VHO between the layers, and neither does it use any of the system specifications from the PHY layer for the RAT decision process.

In this paper, we propose algorithms for RAT selection and VHO in heterogeneous UPANs. Our RAT selection algorithm considers the special characteristics of MB-OFDM and DS-UWB networks as well as the outage probability of the communication links to decide which network is most appropriate for future connection. Technically, we call the combination of these two networks, the *system*. Two different classes of calls are considered and decisions are made based on the type of the call, the device (DEV)'s battery condition and the DEV's mobility. Our VHO procedure indirectly contributes to the overall system load balancing and achieving the grade of service (GoS) requirements. GoS is a measure of system performance based on the new-call and handoff-call blocking probabilities. We have integrated a narrowband interference (NBI) verification policy into the RAT selection and VHO modules to adaptively compensate for the effects of a reduction in GoS. Furthermore, a four-dimensional (4D) Markov chain is used to derive the performance metrics, namely, the new-call and handoff-call block-

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ing probabilities, throughput and average traffic carried by each network. Please note that our proposed RAT selection and VHO algorithms are fundamentally different from conventional algorithms from two points of view. First, we have proposed our algorithms for a new and original scenario of heterogeneous UWB-based wireless personal networks, which is different from conventional heterogeneous network scenarios. Conventional algorithms mostly aim at enhancing the wireless coverage and maintaining the connectivity which differentiate them from our work. Second, our assumptions and triggering conditions are designed based on the technical specifications of DS-UWB and MB-OFDM radios, as well as the type of connection and so are completely different from conventional algorithms. As a result our proposed algorithms are not directly comparable to conventional algorithms. The only algorithm in the literature with partial resemblance to our work is the service-base algorithm in [9], which we use as a benchmark for comparisons in Sect. 4.

The remainder of the paper is organized as follows. In Sect. 2, the system model and the proposed RAT selection and VHO procedures are discussed. Section 3 presents the system analysis based on a 4D Markov model. Section 4 addresses the numerical results and comparisons. Finally, concluding remarks are drawn in Sect. 5.

2. System Model and the Proposed RAT Selection and VHO Procedures

In this section we first describe our system model. Then, we present an overview of the UWB standards' characteristics and describe the proposed modules.

2.1 System Model

We consider a heterogeneous system composed of DS-UWB WPAN (DS-UPAN) and MB-OFDM UWB WPAN (MB-UPAN). Figure 1 illustrates the system model. In terms of topology, each of these two networks can extend its coverage by forming several piconets and different DS-UPAN and MB-UPAN piconets can have overlapping coverage. A piconet consists of several DEVs, with one DEV assuming the role of the piconet coordinator (PNC). In our system, we assume DEVs with low and high mobility, and consider that the DEVs are all multimode and support connection to either of the UPANs. Both networks can accept class-A (requiring high data rate) and class-B (requiring low data rate) calls. Here we use the general term, *call*, for a connection request by a DEV. A call is also classified as being in a battery-critical condition (BC) or in a non-battery-critical condition (NBC). We assume that a session describer module is available in the PNC of each network and is responsible for collecting the aforementioned information and for sensing the presence of NBI in the environment. We also assume that the PNC in the DS-UPAN and the one in the MB-UPAN have the capability to exchange system-related information. Please note that this scenario is different from conventional

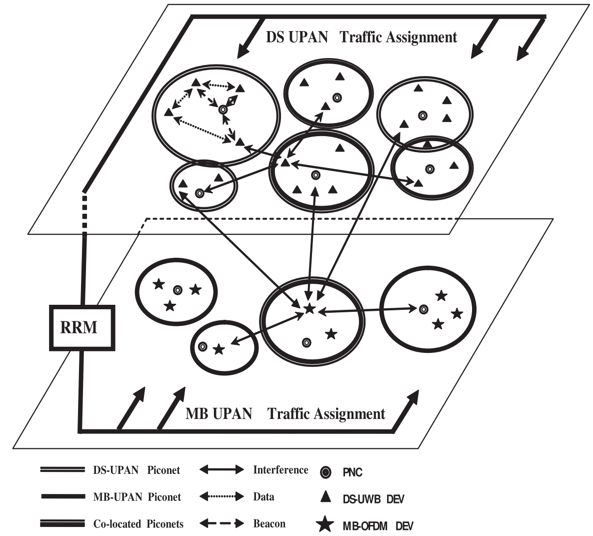

Fig. 1 System model.

infra-structured networks in the sense that only in the initial phase does the PNC communicate with the DEVs, and that for synchronization purpose. In the next phase, different transceiver pairs start their transmission directly. As a practical application for this scenario, we can mention the high-speed cordless connections to peripherals in office environments, instant conferencing and automatic data synchronization on the move.

2.2 DS-UWB and MB-OFDM Characteristics

Before presenting the proposed RAT and VHO algorithms, it is important to recall the distinct characteristics of DS-UWB and MB-OFDM, which are taken into account in our design. Regarding the advantages and disadvantages of these two technologies, in the literature, there are several comparative research works from different perspectives: mutual interference, robustness to multipath, performance, complexity, achievable range-data rate for WPAN applications and effects of mobility. Below, we review some of these characteristics.

- *Mobility*: Not many studies dealt with the impact of mobility on the performance of UWB systems. In [10], the authors investigated the effect of mobility on the performance of DS-UWB, by varying the transmission data rate up to 500 Mbps. It was observed that the average bit error rate of the system degrades for higher data rates in the presence of mobility. In our system, DS-UWB is hence not suitable for DEVs with high mobility and requesting a class-A connection.
- *Interference*: In the presence of NBI, MB-OFDM has an advantage over DS-UWB because of its subcarriers, which give it the ability to use the detect and avoid technique [11]. In this technique, the NBI frequencies are first detected, and the subcarriers related to those frequencies are then nulled.

- *Receiver Performance*: Depending on the technique used at the receiver (matched filter, decision feedback equalizer, etc...), the performance of the two technologies may have a slight difference but, for practical purposes, we can consider the bit error rate performance of both technologies to be similar [1], [2].
- *Data Rate*: Although MB-OFDM is an efficient technology, it can not reach data rates as high as DS-UWB's. This is due to its multiband structure, which restricts the transmission to some smaller subbands of the UWB frequency spectrum [1].
- *Power Consumption*: MB-OFDM technology leads to higher power consumption in comparison to DS-UWB, especially at higher data rates, due to use of fast Fourier transform [1]. Power consumption is a critical issue in certain applications such as wireless sensor networks.

2.3 RAT Selection and Handoff Algorithms

In this section, we first present our RAT selection process, then the proposed VHO procedure is discussed. The goal of these functions is to guarantee stable connection for the DEVs in the system and improved GoS. These two algorithms are designed based on the special characteristics of DS-UPAN and MB-UPAN as reviewed in Sect. 2.2.

2.3.1 RAT Selection

The target network selection for each DEV is done by a cooperation between PNCs in the system. In the proposed algorithm, first the NBI condition is checked and if its value is high, the decision is made regardless of the class of the new call. At the next stage the link outage probability is verified and based on the call class type, mobility condition and battery status, the proper assignment is performed. The detailed procedure is presented in Algorithm 1. In Algorithm 1, P_{NBI} is the probability of existence of NBI in the environment with a decision threshold $\bar{P}_{\mathrm{NBI}}$. In fact, this parameter is measured by estimating the NBI power received by each DEV. There are a variety of techniques for detection and estimation of NBI power in UWB communications. For DS-UPAN, we use an autocorrelation receiver similar to [12] for estimating the NBI power received by the DS-UWB receiver. Later, this value is normalized and compared by the threshold value for decisions in RAT selection and handoff algorithms. For MB-UPAN, we use a receiver structure similar to [13], which estimates the interference power on each subcarrier of the MB-UWB receiver. This estimation is later used to improve the accuracy of the channel estimation as well. In our model $P_{\mathrm{HM}} = \frac{v}{2.5}$ is the probability of the DEV having high mobility with a decision threshold $\bar{P}_{\mathrm{HM}}$ and v is the velocity of the DEV. The degree of mobility can be determined by estimating the DEV's velocity. We assume that the velocity of each DEV can be estimated by the help of an integrated global positioning system (GPS) sensor. We improve the precision by using a Grey prediction filter as in [14] to predict the current value of velocity

Algorithm 1 : RAT Selection

loop
    if new call $\in$ class-A **then**
        if $(P_{\mathrm{NBI}} \geq \bar{P}_{\mathrm{NBI}})$ **then**
            select MB-UPAN **EXIT**
        else if $(\lambda^{\mathrm{DS}}_{A-out} \leq \bar{\lambda}^{\mathrm{DS}}_{A-out}) \wedge (P_{\mathrm{HM}} < \bar{P}_{\mathrm{HM}})$ **then**
            select DS-UPAN **EXIT**
        else if $(\lambda^{\mathrm{MB}}_{A-out} \leq \bar{\lambda}^{\mathrm{MB}}_{A-out}) \wedge (P_{\mathrm{BC}} < \bar{P}_{\mathrm{BC}})$ **then**
            select MB-UPAN **EXIT**
        else
            Reject Call
        end if
    end if
    if new call $\in$ class-B **then**
        if $(P_{\mathrm{NBI}} \geq \bar{P}_{\mathrm{NBI}})$ **then**
            select MB-UPAN
            EXIT
        else if $(\lambda^{\mathrm{MB}}_{A-out} \leq \bar{\lambda}^{\mathrm{MB}}_{A-out}) \wedge (P_{\mathrm{BC}} < \bar{P}_{\mathrm{BC}})$ **then**
            select MB-UPAN **EXIT**
        else if $(\lambda^{\mathrm{DS}}_{B-out} \leq \bar{\lambda}^{\mathrm{DS}}_{B-out})$ **then**
            select DS-UPAN **EXIT**
        else
            Reject Call
        end if
    end if
end loop

based on the previous samples. To form P_{HM}, this value is normalized based on the numerical values considered for the velocity range as explained in Sect. 4. P_{BC} is the probability of the DEV being in the battery-critical condition (BC) with a decision threshold $\bar{P}_{\mathrm{BC}}$ and given by:

$$P_{\mathrm{BC}} = \frac{100 - \textit{Remaining Battery \%}}{100} \tag{1}$$

We assume that the percentage of remaining battery power is provided by the DEV's power management module. Furthermore, $\lambda^{\mathrm{MB}}_{A-out}$ and $\lambda^{\mathrm{MB}}_{B-out}$ are the link outage probabilities in MB-UPAN for class-A and class-B with decision threshold values $\bar{\lambda}^{\mathrm{MB}}_{A-out}$ and $\bar{\lambda}^{\mathrm{MB}}_{B-out}$, respectively. Similarly, $\lambda^{\mathrm{DS}}_{A-out}$ and $\lambda^{\mathrm{DS}}_{B-out}$ are the link outage probabilities in DS-UPAN for class-A and class-B with decision threshold values $\bar{\lambda}^{\mathrm{DS}}_{A-out}$ and $\bar{\lambda}^{\mathrm{DS}}_{B-out}$. In practical systems, the aforementioned outage probabilities can be measured by calculating the percentage of time that the signal strength drops below a certain threshold. For our analytical performance evaluation, in Sect. 3 a procedure is proposed to derive these probabilities. Please note that we use the term *probability* to address the aforementioned parameters in this paper mostly because we employ a probabilistic Markov model to evaluate the performance of our proposed RAT selection and handoff algorithms in Sects. 3 and 4. However, as we explained the practical aspects of these parameters in this section, they are external parameters and obtained directly from the system power management and receiver modules and may not necessarily be probabilistic in nature. Nominal values are chosen for decision thresholds $\bar{P}_{\mathrm{NBI}}$, $\bar{P}_{\mathrm{HM}}$, $\bar{P}_{\mathrm{BC}}$, $\bar{\lambda}^{\mathrm{MB}}_{A-out}$, $\bar{\lambda}^{\mathrm{MB}}_{B-out}$, $\bar{\lambda}^{\mathrm{DS}}_{A-out}$ and $\bar{\lambda}^{\mathrm{DS}}_{B-out}$ in our numerical analysis in Sect. 4. However, for practical systems, optimum values should be chosen with respect to technical specifica-

Algorithm 2 : VHO to MB-UPAN

if $(P^{\mathrm{DS}}_{A-NB} \geq \bar{P}^{\mathrm{DS}}_{A-NB}) \wedge (P^{\mathrm{DS}}_{B-NB} \geq \bar{P}^{\mathrm{DS}}_{B-NB})$
AND
$(P^{\mathrm{DS}}_{A-VB} \geq \bar{P}^{\mathrm{DS}}_{A-VB}) \wedge (P^{\mathrm{DS}}_{B-VB} \geq \bar{P}^{\mathrm{DS}}_{B-VB})$ **then**
  if $P_{\mathrm{NBI}} \geq \bar{P}_{\mathrm{NBI}}$ **then**
    VHO to MB-UPAN
  else if call $\in$ class-A **then**
    if $(P_{\mathrm{HM}} \geq \bar{P}_{\mathrm{HM}}) \wedge (P_{\mathrm{NBC}} \geq \bar{P}_{\mathrm{NBC}})$ **then**
      VHO to MB-UPAN
    end if
  else if call $\in$ class-B **then**
    if $(P_{\mathrm{NBC}} \geq \bar{P}_{\mathrm{NBC}})$ **then**
      VHO to MB-UPAN
    end if
  end if
else
  no action
end if

tions and based on a comprehensive simulation study which is one of our future research objectives and out of the scope of the present paper. Also note that the averaged values of the aforementioned parameters over time are used in the decision process.

2.3.2 VHO Algorithm

The goal in our VHO algorithm design between DS-UPAN and MB-UPAN is two-fold. First, maximizing the end-user satisfaction and the quality of service (QoS) they experience. This is performed by proper reassignment of DEVs to another network by considering their present battery status, degree of mobility and the intensity of NBI which they are exposed to. Second, optimizing the network resources and load balancing by taking into account the actual rates for handoff and new call blocking. The latter can also indirectly lead to increased end-user satisfaction as well. To increase the chance of accepting the handoff calls, we consider channels exclusively reserved for this purpose (guard channels) in both networks. Algorithm 2 presents the VHO procedure to MB-UPAN for calls originating from the DS-UPAN. In Algorithm 2, ($P_{\mathrm{LM}} = 1 - P_{\mathrm{HM}}$) is the probability of the DEV having low mobility with a decision threshold of value ($\bar{P}_{\mathrm{LM}} = 1 - \bar{P}_{\mathrm{HM}}$) and ($P_{\mathrm{NBC}} = 1 - P_{\mathrm{BC}}$) is the probability of the DEV being in non-critical battery condition (NBC) with a decision threshold of value ($\bar{P}_{\mathrm{NBC}} = 1 - \bar{P}_{\mathrm{BC}}$). Further, P^{DS}_{A-NB} and P^{DS}_{B-NB} are the new-call blocking probabilities in DS-UPAN for class-A and class-B with decision thresholds $\bar{P}^{\mathrm{DS}}_{A-NB}$ and $\bar{P}^{\mathrm{DS}}_{B-NB}$, respectively. Corresponding parameters for the handoff-call blocking probabilities are P^{DS}_{A-VB}, $\bar{P}^{\mathrm{DS}}_{A-VB}$, P^{DS}_{B-VB} and $\bar{P}^{\mathrm{DS}}_{B-VB}$. Algorithm 3 presents the VHO procedure to DS-UPAN for calls originating from MB-UPAN. In Algorithm 3, P^{DS}_{A-NB} and P^{DS}_{B-NB} are the new-call blocking probabilities in DS-UPAN for class-A and class-B with decision thresholds $\bar{P}^{\mathrm{DS}}_{A-NB}$ and $\bar{P}^{\mathrm{DS}}_{B-NB}$, respectively. Corresponding parameters for the handoff-call blocking probabilities are P^{DS}_{A-VB}, $\bar{P}^{\mathrm{DS}}_{A-VB}$, P^{DS}_{B-VB} and $\bar{P}^{\mathrm{DS}}_{B-VB}$.

Algorithm 3 : VHO to DS-UPAN

if $(P^{\mathrm{MB}}_{A-NB} \geq \bar{P}^{\mathrm{MB}}_{A-NB}) \wedge (P^{\mathrm{MB}}_{B-NB} \geq \bar{P}^{\mathrm{MB}}_{B-NB})$
AND
$(P^{\mathrm{MB}}_{A-VB} \geq \bar{P}^{\mathrm{MB}}_{A-VB}) \wedge (P^{\mathrm{MB}}_{B-VB} \geq \bar{P}^{\mathrm{MB}}_{B-VB})$ **then**
  if $P_{\mathrm{BC}} \geq \bar{P}_{\mathrm{BC}}$ **then**
    VHO to DS-UPAN
  end if
else
  no action
end if

3. 4D Markovian Performance Analysis

In this section, we use Markov based analysis to evaluate the performance of the two proposed modules. We assume one DS-UPAN and one MB-UPAN co-located in the same coverage area. We also assume that a DEV is connected only to one of these networks during its active session. In order to improve the GoS, we allocate guard channels to both networks. There are a total number of C_{DS} available channels in DS-UPAN, from which C^{h}_{DS} channels are reserved for handoff calls. For MB-UPAN, these values are C_{MB} and C^{h}_{MB}, respectively.

The class-A and class-B calls are considered to have independent Poisson arrival rates. The corresponding call arrival rates are denoted λ_A and λ_B, respectively. We consider an exponential distribution for the channel holding time for both types of calls with a mean of $1/\mu_A$ and $1/\mu_B$ for DS-UPAN and MB-UPAN, respectively.

Based on the above assumptions, the system can be modelled as a birth-death process and a Markov-based analysis can be performed. Here we consider a 4D Markov chain with states defined as $P(a_1, b_1, a_2, b_2)$ where a_1 is the number of class-A calls in MB-UPAN, b_1 is the number of class-B calls in MB-UPAN, a_2 is the number of class-A calls in DS-UPAN and b_2 is the number of class-B calls in DS-UPAN. Both networks only accept new calls if $(a_1 + b_1) \leq C^{T}_{\mathrm{MB}}$ and $(a_2 + b_2) \leq C^{T}_{\mathrm{DS}}$, where $C^{T}_{\mathrm{MB}} = C_{\mathrm{MB}} - C^{h}_{\mathrm{MB}}$ and $C^{T}_{\mathrm{DS}} = C_{\mathrm{DS}} - C^{h}_{\mathrm{DS}}$.

3.1 State Transitions

Recalling the birth-death process properties, the only possible transitions are to neighboring states. There are a total of 24 possible transitions to or from state $P(a_1, b_1, a_2, b_2)$ in our Markov chain model. Figure 2 shows the possible birth and death transitions from and to state $P(a_1, b_1, a_2, b_2)$, and Fig. 3 shows the possible handoff transitions from and to this state. This assumption is valid because of the memoryless property of the arrival process and the exponential distribution of the channel holding time. The system is working under steady-state conditions. In the following, we present the possible transitions to or from state $P(a_1, b_1, a_2, b_2)$ and the corresponding transition rates, i.e., $C_1, ..., C_{12}$ and $D_1, ..., D_{12}$.

1- $P(a_1, b_1, a_2, b_2) \longrightarrow P(a_1 + 1, b_1, a_2, b_2)$ In this case, the

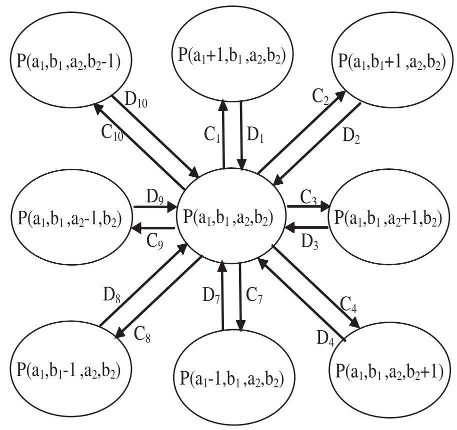

Fig. 2 Possible birth and death transitions from and to state $P(a_1, b_1, a_2, b_2)$.

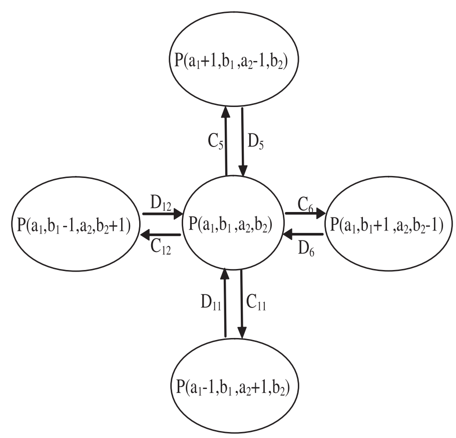

Fig. 3 Possible handoff transitions from and to state $P(a_1, b_1, a_2, b_2)$.

number of class-A calls being served by the MB-UPAN is increased by one if $0 \leq (a_1 + b_1) < C^T_{\mathrm{MB}}$. The transition rate, C_1, is given by:

$$C_1 = \lambda_A P_{\mathrm{NBI}}(P_{\mathrm{HM}} + P_{\mathrm{NBC}}) \left(1 - \left(\lambda^{\mathrm{MB}}_{A-out}\right)^{C^T_{\mathrm{MB}} - a_1 - 1}\right). \tag{2}$$

As mentioned earlier, $\lambda^{\mathrm{MB}}_{A-out}$ is the link outage probability for class-A in the MB-UPAN, which imposes the channel quality constraint on our proposed RAT selection policy and it is defined as the event that the signal strength is below a certain level. To calculate the outage probability of class-A in MB-UPAN, we consider a reference DEV with class-A connection in MB-UPAN and similar to [15], $\lambda^{\mathrm{MB}}_{A-out}$ is written as:

$$\lambda^{\mathrm{MB}}_{A-out} = \sum_{m=0}^{C_{\mathrm{DS}}-1} \sum_{n=1}^{C_{\mathrm{MB}}-1} \lambda^{\mathrm{MB}}_{A-out|n,m} \binom{C_{\mathrm{MB}}-1}{n} \binom{C_{\mathrm{DS}}-1}{m} \times \mu^n_{\mathrm{MB}} \mu^m_{\mathrm{DS}} (1-\mu_{\mathrm{MB}})^{C_{\mathrm{MB}}-1-n} (1-\mu_{\mathrm{DS}})^{C_{\mathrm{DS}}-1-m}, \tag{3}$$

where μ_{DS} is the probability of finding active interfering DEVs in the DS-UPAN, transmitting on the same time slot as the reference DEV (n=0), and μ_{MB} is the probability of finding active interfering DEVs in the MB-UPAN, transmitting on the same time slot as the reference DEV. Further details on calculation of $\lambda^{\mathrm{MB}}_{A-out|n,m}$ are provided in [16]. It is important to mention that in (3), we sum up the effect of all interferers in the DS-UPAN and the MB-UPAN for both types of calls (class-A and class-B). In fact, λ_A is the sum arrival rate at the MB-UPAN and DS-UPAN networks, i.e., we have $\lambda_A = C_1 + C_3$. The same argument stands for λ_B.

2- $P(a_1, b_1, a_2, b_2) \longleftarrow P(a_1 + 1, b_1, a_2, b_2)$ In this case the number of class-A calls being served by MB-UPAN is decreased by one if $a_1 > 0$. The transition rate, D_1, is given by:

$$D_1 = (a_1 + 1)\mu_A. \tag{4}$$

3- $P(a_1, b_1, a_2, b_2) \longrightarrow P(a_1, b_1 + 1, a_2, b_2)$ In this case, the number of class-B calls being served by the MB-UPAN is increased by one if $0 \leq (a_1 + b_1) < C^T_{\mathrm{MB}}$. The transition rate, C_2, is given by:

$$C_2 = \lambda_B P_{\mathrm{NBI}}(P_{\mathrm{LM}} + P_{\mathrm{NBC}}) \left(1 - \left(\lambda^{\mathrm{MB}}_{B-out}\right)^{C^T_{\mathrm{MB}} - b_1 - 1}\right), \tag{5}$$

where $\lambda^{\mathrm{MB}}_{B-out}$ is the link outage probability for class-B calls in MB-UPAN.

4- $P(a_1, b_1, a_2, b_2) \longleftarrow P(a_1, b_1 + 1, a_2, b_2)$ In this case, the number of class-B calls being served by the MB-UPAN is decreased by one if $b_1 > 0$. The transition rate, D_2, is given by:

$$D_2 = (b_1 + 1)\mu_B. \tag{6}$$

5- $P(a_1, b_1, a_2, b_2) \longrightarrow P(a_1, b_1, a_2 + 1, b_2)$ In this case, the number of class-A calls being served by the DS-UPAN is increased by one if $0 \leq (a_2 + b_2) < C^T_{\mathrm{DS}}$. The transition rate, C_3, is given by:

$$C_3 = \lambda_A - C_1. \tag{7}$$

6- $P(a_1, b_1, a_2, b_2) \longleftarrow P(a_1, b_1, a_2 + 1, b_2)$ In this case the number of class-A calls being served by DS-UPAN is decreased by one if $a_2 > 0$. The transition rate, D_3, is given by:

$$D_3 = (a_2 + 1)\mu_A. \tag{8}$$

7- $P(a_1, b_1, a_2, b_2) \longrightarrow P(a_1, b_1, a_2, b_2 + 1)$ In this case, the number of class-B calls being served by the DS-UPAN is increased by one if $0 \leq (a_2 + b_2) < C^T_{\mathrm{DS}}$. The transition rate, C_4, is given by:

$$C_4 = \lambda_B - C_2. \tag{9}$$

8- $P(a_1, b_1, a_2, b_2) \longleftarrow P(a_1, b_1, a_2, b_2 + 1)$ In this case, the number of class-B calls being served by the DS-UPAN is decreased by one if $b_2 > 0$. The transition rate, D_3, is given by:

$$D_4 = (b_2 + 1)\mu_B. \tag{10}$$

9- $P(a_1, b_1, a_2, b_2) \longrightarrow P(a_1+1, b_1, a_2-1, b_2)$ In this case, the number of class-A VHO calls in the MB-UPAN is increased by one if $a_2 > 0$ and $0 \leq (a_1 + b_1) < C_{MB}$. The VHO rate for MB-UPAN, C_5, is defined by:

$$C_5 = \left(\lambda_A\left(1 - P^{DS}_{A-NB}\right) + C_{11}\left(1 - P^{DS}_{A-VB}\right)\right) \times P_{NBI}(P_{HM} + P_{NBC})\left(1 - \left(\lambda^{MB}_{A-out}\right)^{C^T_{MB}-a_1-1}\right), \tag{11}$$

10- $P(a_1, b_1, a_2, b_2) \longleftarrow P(a_1 + 1, b_1, a_2 - 1, b_2)$ In this case, the number of class-A VHO calls in the DS-UPAN is increased by one if $a_1 > 0$ and $0 \leq (a_1 + b_1) < C_{DS}$. The VHO rate for DS-UPAN, D_5, is defined by:

$$D_5 = \left(C_3\left(1-P^{MB}_{A-NB}\right)+C_5\left(1-P^{MB}_{A-VB}\right)\right)\left(1-\left(\lambda^{DS}_{A-out}\right)^{C^T_{DS}-a_2}\right), \tag{12}$$

where λ^{DS}_{A-out} is the link outage probability for class-A in DS-UPAN.

11- $P(a_1, b_1, a_2, b_2) \longrightarrow P(a_1, b_1 + 1, a_2, b_2 - 1)$ In this case, the number of class-B VHO calls in the MB-UPAN is increased by one if $b_2 > 0$ and $0 \leq (a_1 + b_1) < C_{MB}$. The VHO rate for MB-UPAN, C_6, is defined by:

$$C_6 = \left(\lambda_B\left(1 - P^{DS}_{B-NB}\right) + C_{12}\left(1 - P^{DS}_{B-VB}\right)\right) \times P_{NBI}(P_{LM} + P_{NBC})\left(1 - \left(\lambda^{MB}_{B-out}\right)^{C^T_{MB}-b_1-1}\right), \tag{13}$$

12- $P(a_1, b_1, a_2, b_2) \longleftarrow P(a_1, b_1 + 1, a_2, b_2 - 1)$ In this case, the number of class-B VHO calls in the DS-UPAN is increased by one if $b_1 > 0$ and $0 \leq (a_1 + b_1) < C_{DS}$. The VHO rate for DS-UPAN, D_6, is defined by:

$$D_6 = \left(C_4\left(1-P^{MB}_{B-NB}\right)+C_6\left(1-P^{MB}_{B-VB}\right)\right)\left(1-\left(\lambda^{DS}_{B-out}\right)^{C^T_{DS}-b_2}\right), \tag{14}$$

where λ^{DS}_{B-out} is the link outage probability for class-B in DS-UPAN. As observed in (11) and (13), the VHO rate depends on the handoff and new-call blocking probabilities. There are a variety of other approaches to estimate the VHO rate. For further information on calculation of the handoff rate, the reader is referred to [6], [17]. Finally, the transition rates $C_7, ..., C_{12}$ and $D_7, ..., D_{12}$ can be derived as explained for $C_1, ..., C_6$ and $D_1, ..., D_6$ in (2) to (14).

3.2 Steady State Balance Equations

It is rather impractical to write all the balance equations in this paper and it is hard to summarize balance transition relations given that there are too many state boundaries for such a 4D Markov chain. Therefore, we divide the state boundaries into three main groups and give an example for each.

Case 1: In the states where $0 < (a_1 + b_1) < C^T_{MB}$ and $0 < (a_2 + b_2) < C^T_{DS}$, both the handoff and the new-calls are admitted into the system. The steady state balance equations for this case are written as:

$$\begin{aligned}
&(C_1 + \cdots + C_{12})P(a_1, b_1, a_2, b_2) = \\
&D_1P(a_1+1, b_1, a_2, b_2)+D_2P(a_1, b_1+1, a_2, b_2) \\
&+D_3P(a_1, b_1, a_2+1, b_2)+D_4P(a_1, b_1, a_2, b_2+1) \\
&+D_5P(a_1+1, b_1, a_2-1, b_2)+D_6P(a_1, b_1+1, a_2, b_2-1) \\
&+D_7P(a_1-1, b_1, a_2, b_2)+D_8P(a_1, b_1-1, a_2, b_2) \\
&+D_9P(a_1, b_1, a_2-1, b_2)+D_{10}P(a_1, b_1, a_2, b_2-1) \\
&+D_{11}P(a_1-1, b_1, a_2+1, b_2)+D_{12}P(a_1, b_1-1, a_2, b_2+1).
\end{aligned} \tag{15}$$

Case 2: In the states where $C^T_{MB} \leq (a_1 + b_1) < C_{MB}$ and $C^T_{DS} \leq (a_2 + b_2) < C_{DS}$, only handoff calls are admitted and the steady state balance equations are written as:

$$\begin{aligned}
&(C_5 + \cdots + C_{12})P(a_1, b_1, a_2, b_2) = \\
&D_5P(a_1+1, b_1, a_2-1, b_2)+D_6P(a_1, b_1+1, a_2, b_2-1) \\
&+D_7P(a_1-1, b_1, a_2, b_2)+D_8P(a_1, b_1-1, a_2, b_2) \\
&+D_9P(a_1, b_1, a_2-1, b_2)+D_{10}P(a_1, b_1, a_2, b_2-1) \\
&+D_{11}P(a_1-1, b_1, a_2+1, b_2)+D_{12}P(a_1, b_1-1, a_2, b_2+1).
\end{aligned} \tag{16}$$

Case 3: Border states, where any dimension of the state can terminate in one of the values: 0, C^T_{MB}, C^T_{DS}, C_{MB} or C_{DS}, e.g., the balance equations for state $(0, 0, 0, 0)$ is given by:

$$\begin{aligned}
&(C_1 + C_2 + C_3 + C_4)P(a_1, b_1, a_2, b_2) = \\
&D_1P(a_1 + 1, b_1, a_2, b_2) + D_2P(a_1, b_1 + 1, a_2, b_2) \\
&+ D_3P(a_1, b_1, a_2 + 1, b_2) + D_4P(a_1, b_1, a_2, b_2 + 1)
\end{aligned} \tag{17}$$

and for state $(0, C_{MB}, 0, C_{DS})$, by:

$$\begin{aligned}
&(C_7 + C_8 + C_9 + C_{10})P(a_1, b_1, a_2, b_2) = \\
&+ D_7P(a_1 - 1, b_1, a_2, b_2) + D_8P(a_1, b_1 - 1, a_2, b_2) \\
&+ D_9P(a_1, b_1, a_2 - 1, b_2) + D_{10}P(a_1, b_1, a_2, b_2 - 1).
\end{aligned} \tag{18}$$

The Markov chain normalization equation is given by:

$$\sum_{b_2=0}^{C_{DS}-a_2} \sum_{a_2=0}^{C_{DS}} \sum_{b_1=0}^{C_{MB}-a_1} \sum_{a_1=0}^{C_{MB}} P(a_1, b_1, a_2, b_2) = 1. \tag{19}$$

3.3 Deriving the Performance Metrics

The steady state probabilities can be derived using the balance equations, some of which are mentioned above, and the normalization constraint given in (19). The total number of possible states is equal to:

$$N_S = \sum_{i=0}^{C_{\mathrm{MB}}} (C_{\mathrm{MB}} - i). \sum_{j=0}^{C_{\mathrm{DS}}} (C_{\mathrm{DS}} - j). \tag{20}$$

As a result, the transition probability matrix will be of dimension $N_S \times N_S$.

After calculation of the system's steady state probabilities, the performance metrics can easily be derived.

In the heterogeneous system, a handoff call is blocked when there are no more free channels available at the destination network; or from an analytical point of view we can say a handoff blocking occurs when the system is urged to enter an unfeasible state. As a result, we can write the system's handoff blocking probability as:

$$\begin{aligned} P_{VB} =& P^{\mathrm{DS}}_{B-VB} + P^{\mathrm{DS}}_{A-VB} + P^{\mathrm{MB}}_{B-VB} + P^{\mathrm{MB}}_{A-VB} \\ =& \sum_{a_2=0}^{C_{\mathrm{DS}}} \sum_{b_1=0}^{C_{\mathrm{MB}}-a_1} \sum_{a_1=0}^{C_{\mathrm{MB}}} P(a_1, b_1, a_2, C_{\mathrm{DS}} - a_2) \\ &+ \sum_{b_2=0}^{C_{\mathrm{DS}}} \sum_{b_1=0}^{C_{\mathrm{MB}}-a_1} \sum_{a_1=0}^{C_{\mathrm{MB}}} P(a_1, b_1, C_{\mathrm{DS}} - b_2, b_2) \\ &+ \sum_{b_2=0}^{C_{\mathrm{DS}}-a_2} \sum_{a_2=0}^{C_{\mathrm{DS}}} \sum_{a_1=0}^{C_{\mathrm{MB}}} P(a_1, C_{\mathrm{MB}} - a_1, a_2, b_2) \\ &+ \sum_{b_2=0}^{C_{\mathrm{DS}}-a_2} \sum_{a_2=0}^{C_{\mathrm{DS}}} \sum_{b_1=0}^{C_{\mathrm{MB}}} P(C_{\mathrm{MB}} - b_1, b_1, a_2, b_2). \end{aligned} \tag{21}$$

Similarly, the blocking probability of new-calls occurs when the system is urged to enter unfeasible states or states considered just for handoff. This probability is given by:

$$\begin{aligned} P_{NB} =& P^{\mathrm{DS}}_{B-NB} + P^{\mathrm{DS}}_{A-NB} + P^{\mathrm{MB}}_{B-NB} + P^{\mathrm{MB}}_{A-NB} \\ =& \sum_{x=0}^{C^h_{\mathrm{DS}}} \left(\sum_{a_2=0}^{C^T_{\mathrm{DS}}+x} \sum_{b_1=0}^{C_{\mathrm{MB}}-a_1} \sum_{a_1=0}^{C_{\mathrm{MB}}} P(a_1, b_1, a_2, C_{\mathrm{DS}} - a_2) \right) \\ &+ \sum_{x=0}^{C^h_{\mathrm{DS}}} \left(\sum_{b_2=0}^{C^T_{\mathrm{DS}}+x} \sum_{b_1=0}^{C_{\mathrm{MB}}-a_1} \sum_{a_1=0}^{C_{\mathrm{MB}}} P(a_1, b_1, C_{\mathrm{DS}} - b_2, b_2) \right) \\ &+ \sum_{x=0}^{C^h_{\mathrm{MB}}} \left(\sum_{b_2=0}^{C_{\mathrm{DS}}-a_2} \sum_{a_2=0}^{C_{\mathrm{DS}}} \sum_{a_1=0}^{C^T_{\mathrm{MB}}+x} P(a_1, C_{\mathrm{MB}} - a_1, a_2, b_2) \right) \\ &+ \sum_{x=0}^{C^h_{\mathrm{MB}}} \left(\sum_{b_2=0}^{C_{\mathrm{DS}}-a_2} \sum_{a_2=0}^{C_{\mathrm{DS}}} \sum_{b_1=0}^{C^T_{\mathrm{MB}}+x} P(C_{\mathrm{MB}} - b_1, b_1, a_2, b_2) \right). \end{aligned} \tag{22}$$

The total throughput of the system can be written as:

$$\begin{aligned} R_T =& \sum_{b_2=0}^{C_{\mathrm{DS}}-a_2} \sum_{a_2=0}^{C_{\mathrm{DS}}} \sum_{b_1=0}^{C_{\mathrm{MB}}-a_1} \sum_{a_1=0}^{C_{\mathrm{MB}}} P(a_1, b_1, a_2, b_2) \\ &\times \left(a_1 R^{\mathrm{MB}}_A + b_1 R^{\mathrm{MB}}_B + a_2 R^{\mathrm{DS}}_A + b_2 R^{\mathrm{DS}}_B \right), \end{aligned} \tag{23}$$

where R^{MB}_A is the basic channel data rate of class-A in MB-UPAN, R^{MB}_B is the one for class-B in MB-UPAN, R^{DS}_A is the basic channel data rate of class-A in DS-UPAN and R^{DS}_B is the one for class-B in DS-UPAN. Finally, the average number of DEVs (class-A and class-B) in the system, which indicates the system's carried traffic is given by:

$$\begin{aligned} T_T =& \sum_{b_2=0}^{C_{\mathrm{DS}}-a_2} \sum_{a_2=0}^{C_{\mathrm{DS}}} \sum_{b_1=0}^{C_{\mathrm{MB}}-a_1} \sum_{a_1=0}^{C_{\mathrm{MB}}} P(a_1, b_1, a_2, b_2) \\ &\times (a_1 + b_1 + a_2 + b_2). \end{aligned} \tag{24}$$

4. Numerical Results

Throughout this section, we present numerical results regarding the analysis of our Markov-based RRM approaches. To simplify the evaluation process, we consider one DS-UPAN and one MB-UPAN with $C_{\mathrm{DS}} = 3$ and $C_{\mathrm{MB}} = 3$ channels, respectively. However, the system is easily scalable for higher values of piconets and channels. In each network, one channel is reserved for handoff calls ($C^h_{\mathrm{DS}} = C^h_{\mathrm{MB}} = 1$). A mobility model for 2D indoor environments similar to [10] is considered and typical values for the speed of low and high mobility DEVs are chosen to be 0.6 m/s and 2 m/s, respectively. We assume that each class (A, B) adapts its transmission rate according to the network it is connected to, namely, 110 Mbps for MB-UPAN and 1000 Mbps for DS-UPAN. The numerical values assumed for the other parameters are defined by: $P_{NBI} = 0.1$, $P_{BC} = 0.2$, $P_{LM} = 0.2$, $\mu_A = \mu_B = 0.1$, unless otherwise stated.

An iterative algorithm is used to calculate the VHO rates in (11) and (13), starting from an initial value for C_5 and C_6. As previously mentioned, to compute the link outage probability, we consider a general analytical model that accounts for the fading effect based on a Nakagami-*m* fading model [9], [18]. The provided results are compared with the service-based RAT selection strategy presented in [9] where the selection is only based on the type of call. We chose this algorithm because of its partial resemblance, which makes it comparable to our proposed algorithm.

Figure 4 and Fig. 5 show the VHO blocking and new-call blocking probabilities versus class-A call arrival rate for the DS-UPAN and the MB-UPAN and $\lambda_B = 0.1$. It is obvious that our proposed algorithm has a better performance than the service-based approach. Our algorithm uses more information in the decision process for the RAT selection, such as the link outage probability which indirectly contributes to reducing the blocking probability for VHO as well as for new calls. To investigate the effect of an increase in class-B call arrival rate, we set this value to 0.8 and in Fig. 6 and Fig. 7 we derive the similar results as in

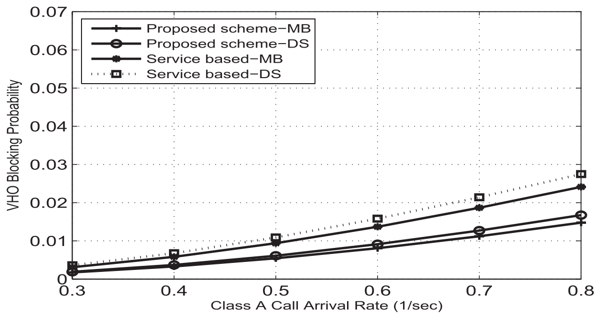

Fig. 4 VHO block. prob. vs. class-A call arrival rate (λ_A), $\lambda_B = 0.1$.

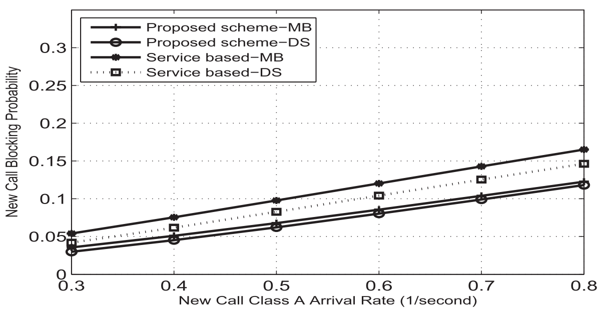

Fig. 5 New-call block. prob. vs. class-A call arrival rate (λ_A), $\lambda_B = 0.1$.

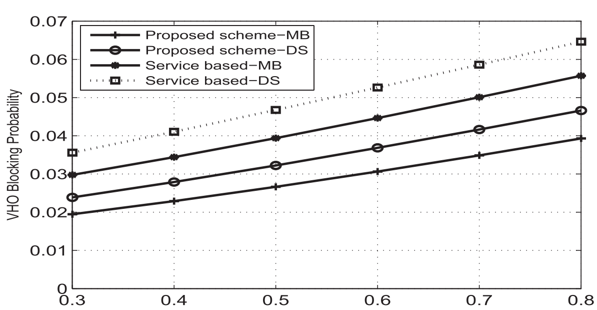

Fig. 6 VHO block. prob. vs. class-A call arrival rate (λ_A), $\lambda_B = 0.8$.

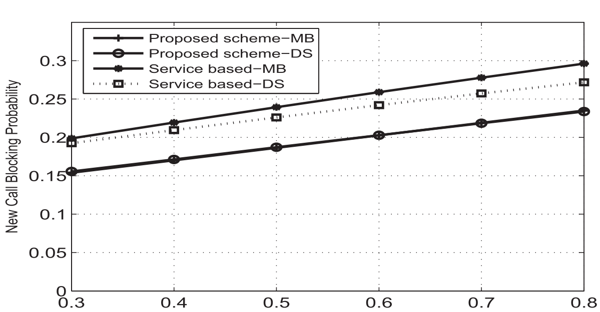

Fig. 7 New-call block. prob. vs. class-A call arrival rate (λ_A), $\lambda_B = 0.8$.

Fig. 4 and Fig. 5 for the VHO blocking and new-call blocking probabilities, respectively. In Fig. 6, we observe that an increase of 0.7 unit in class-B call arrival rate results in an increase of about 3 percent in VHO blocking probability for service based algorithm but this increase is only 2 percent for our proposed algorithm. We also notice that is higher

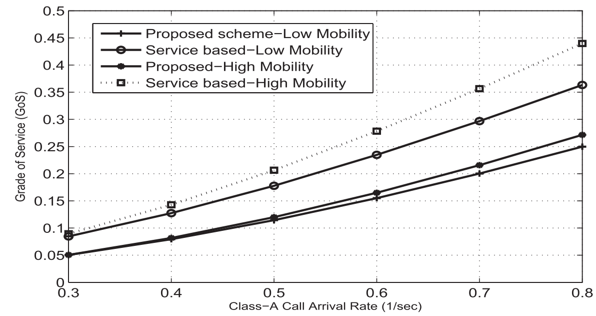

Fig. 8 GoS vs. class-A call arrival rate.

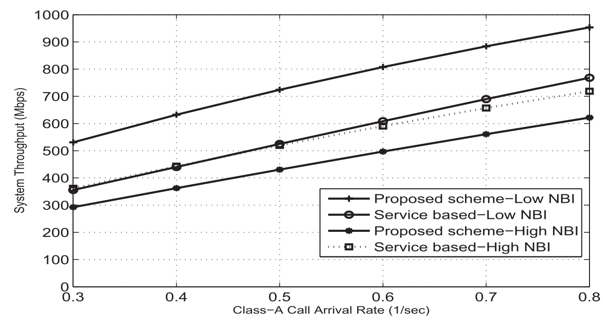

Fig. 9 Total system throughput vs. class-A call arrival rate.

values of class-B call arrival rates, the difference between DS-UPAN and the MB-UPAN performance increases, however it is less divergent. Similarly, as we observe in Fig. 7, the increase of 0.7 unit in class-B call arrival rate results in an increase of about 15 percent in new-call blocking probability for service-based algorithm, while this increase is only 10 percent for our proposed algorithm. For new-call blocking probability, this increase reduces the difference between DS-UPAN and the MB-UPAN performance for our algorithm, while this difference remains the same for the service-based algorithm.

Figure 8 shows the GoS versus class-A call arrival rate. Technically, we define the GoS measure of the overall system performance by GoS=$P_{NB} + \alpha P_{VB}$, where $\alpha > 1$ is a weighting factor used to put more importance on handoff blocking probability (e.g., 10). Indeed, blocking a connection already in progress is usually more annoying than blocking a new call. From an overall system performance point of view, our algorithm still leads a better performance. It is also observed that at higher mobility the performance degrades to some extent. This can be explained by the increase in the rate of VHO at high speeds. However, using the proposed algorithm the performance degradation is less compared to the service-based approach. Figure 9 shows the total system throughput versus class-A call arrival rate. For lower probability of NBI in the environment ($P_{\mathrm{NBI}} = 0.1$), our algorithm gives better performance. This is indirectly related to its better GoS performance. However, in the case of higher probability of NBI ($P_{\mathrm{NBI}} = 0.6$), a slight degradation is observed. Indeed, to improve the GoS, our algorithm forwards a larger number of connections to the MB-UPAN

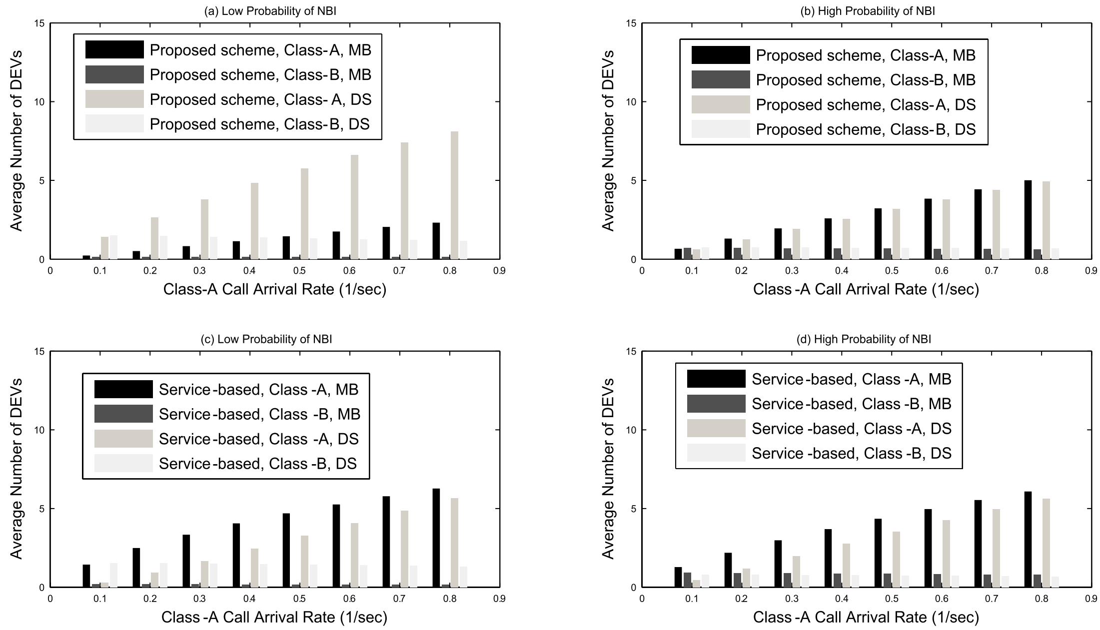

Fig. 10 Average number of DEVs versus class-A call arrival rate for (a) the proposed scheme and low probability of NBI, (b) the proposed scheme and high probability of NBI, (c) the service-based scheme and low probability of NBI, and (d) the service-based scheme and higher probability of NBI.

in this case, which causes a reduction in system throughput because of the lower data rate per channel for MB-UPAN in comparison with DS-UPAN.

Finally, Fig. 10 shows the average number of DEVs (or the carried traffic) versus class-A new-call arrival rate for (a) the proposed algorithm in the presence of lower probability of NBI ($P_{\mathrm{NBI}} = 0.1$), (b) the proposed algorithm in the presence of higher probability of NBI ($P_{\mathrm{NBI}} = 0.6$), (c) the service-based algorithm with $P_{\mathrm{NBI}} = 0.1$, and (d) the service-based algorithm with $P_{\mathrm{NBI}} = 0.6$. As expected, the average traffic carried by the MB-UPAN increases when using the proposed algorithm, under high probability for NBI.

5. Conclusion

Two RRM modules for RAT selection and VHO procedure in heterogeneous UWB-based WPANs (UPANs) were proposed in this paper. The RAT selection algorithm considers the specifications of two types of UPANs (DS-UPAN and MB-UPAN) and, based on the link outage probability and the existence of NBI in the environment, decides to which network a DEV should be connected. The proposed VHO decision procedure receives real-time information of the new-call and handoff-call blocking probabilities and aims at balancing the load between the two networks. An analytical method based on 4D Markov modeling was presented to assess the performance of our proposed RAT selection and VHO algorithms. It was attested that our algorithm has a better performance in terms of reducing the new-call and handoff-call blocking probabilities, and improving the GoS. For lower intensities of NBI in the environment, the proposed algorithm improves the system throughput significantly, whereas its performance is slightly less than service-based approaches at higher probabilities given that our algorithms tend to allocate more calls to the MB-UPAN to improve the GoS in this case. Considering the system's average carried traffic for the MB-UPAN, our algorithms perform better under higher probability of NBI in the environment.

References

[1] A. Batra, J. Balakrishnan, et al., "Multi-band OFDM physical layer proposal for IEEE 802.15 task group 3a," IEEE P802.15-03/268r3, March 2004.

[2] R. Fisher, R. Kohno, et al., "DS-UWB physical layer submission to 802.15 task group 3a," IEEE P802.15- 04/0137r4, Jan. 2005.

[3] I. Stojmenovic, Handbook of wireless networks and mobile computing, Wiley, 2002.

[4] E. Stevens-Navarro, Y. Lin, and V. Wong, "An MDP-based vertical handoff decision algorithm for heterogeneous wireless networks," IEEE Trans. Veh. Technol., vol.57, no.2, pp.1243–1254, March 2008.

[5] A. Mehbodniya and J. Chitizadeh, "User location estimation in wireless networks with application to vertical handoff using pattern recognition," Proc. 10th IEEE Symposium on Computers and Communications (ISCC 2005), pp.315–320, June 2005.

[6] A.H. Zahran, B. Liang, and A. Saleh, "Mobility modeling and performance evaluation of heterogeneous wireless networks," IEEE Trans. Mobile Comput., vol.7, no.8, pp.1041–1056, Aug. 2008.

[7] J. Wang, Q.-A. Zeng, and D. Agrawal, "Performance analysis of a preemptive and priority reservation handoff scheme for integrated service-based wireless mobile networks," IEEE Trans. Mobile Comput., vol.2, no.1, pp.65–75, Jan.-March 2003.

[8] J. McNair and F. Zhu, "Vertical handoffs in fourth-generation multinetwork environments," IEEE Trans. Wireless Commun., vol.11, no.3, pp.8–15, June 2004.

[9] X. Gelabert, J. Perez-Romero, O. Sallent, and R. Agusti, "A Markovian approach to radio access technology selection in heterogeneous

multiaccess/multiservice wireless networks," IEEE Trans. Mobile Comput., vol.7, no.10, pp.1257–1270, Oct. 2008.

[10] F. De Rango, F. Veltri, and S. Marano, "The impact of mobility users on DS-UWB system performance," Proc. Canadian Conference on Electrical and Computer Engineering (CCECE 2008), pp.1667–1670, May 2008.

[11] J. Lansford, "Detect and avoid (DAA) for UWB: Implementation issues and challenges," Proc. IEEE 18th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2007), pp.1–5, Sept. 2007.

[12] Y. Alemseged, H. Harada, and K. Witrisal, "Detection and identification of nbi for multichannel uwb autocorrelation receivers," Proc. IEEE Wireless Communications and Networking Conference (WCNC 2009), pp.1–6, April 2009.

[13] N. Hadaschik, I. Zakia, G. Ascheid, and H. Meyr, "Joint narrowband interference detection and channel estimation for wideband ofdm," Proc. 13th European Wireless Conference, pp.1–7, April 2007.

[14] X. Liu and L. Jiang, "A novel vertical handoff algorithm based on fuzzy logic in aid of grey prediction theory in wireless heterogeneous networks," J. Shanghai Jiaotong University (Science), vol.17, no.1, pp.25–30, 2012.

[15] J.-P. Linnartz, "Exact analysis of the outage probability in multiple-user mobile radio," IEEE Trans. Commun., vol.40, no.1, pp.20–23, Jan. 1992.

[16] A. Mehbodniya and S. Aissa, "Outage and BER analysis for ultrawideband-based WPAN in Nakagami-*m* fading channels," IEEE Trans. Veh. Technol., vol.60, no.7, pp.3515–3520, Sept. 2011.

[17] D. Sarkar, T. Jewell, and S. Ramakrishnan, "Convergence in the calculation of the handoff arrival rate: A log-time iterative algorithm," EURASIP Journal on Wireless Communications and Networking, pp.1–11, 2006.

[18] E. Vanem, S. Svaet, and F. Paint, "Effects of multiple access alternatives in heterogeneous wireless networks," Proc. IEEE Wireless Communications and Networking Conference (WCNC 2003), pp.1696–1700, 2003.

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