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Call admission control for wireless mesh network based on power interference modeling using directional antenna

Saravanan Kandasamy[1] · Carlos Marques[2] · Tania Calçada[3] · Manuel Ricardo[1] · Ricardo Matos[2] · Susana Sargento[2]

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Abstract Interference is a fundamental issue in wireless mesh networks (WMNs) and it seriously affects the network performance. In this paper we characterize the power interference in IEEE 802.11 CSMA/CA based wireless mesh networks using directional antennas. A model based centralized call admission control (CAC) scheme is proposed which uses physical collision constraints, and transmitter-side, receiver-side and when-idle protocol collision prevention constraints. The CAC assists to manage requests from users depending on the available bandwidth in the network: when a new virtual link establishment request from a user is accepted into the network, resources such as interface, bandwidth, transmission power and channel are allocated in the participating nodes and released once the session is completed. The proposed CAC is also able to contain the interference in the WMN by managing the transmission power of nodes.

Keywords Directional antenna · Interference modeling · Call admission control · Wireless mesh networks

1 Introduction

We address wireless mesh networks (WMNs) consisting of IEEE 802.11 based access points (nodes) organized in a mesh topology. These nodes are static, have one or more network interfaces attached to them and operate both as hosts and packet forwarders. WMNs are low cost, adaptable, and adequate to complement the coverage of other access networks [1–3]. Due to these characteristics, WMNs are becoming popular and they are a good solution to support scenarios with many obstructions such as specific parts of a city [4].

Omnidirectional antenna (OA) is the only antenna supported by the IEEE 802.11 standard [5]. Nevertheless, nowadays many IEEE 802.11 based WMNs have been setup to support directional antennas (DA). DA is attractive for WMN [6–8] for a number of reasons, including the following: (1) a node is enabled to transmit at desired directions and reducing interference on unwanted directions; (2) more simultaneous communications can be initiated by the nodes in the same channel and region as a result of higher spatial reuse factor for DA; (3) due to the higher antenna gain, a source node in a multihop WMN is able to reach its destination node in a potentially lower number of hops because of the increased transmission range. For these reasons DA may be preferred to OA in some of the WMN scenarios.

✉ Saravanan Kandasamy
kandasamy@inesctec.pt

Carlos Marques
car.manuel@ua.pt

Tania Calçada
tcalcada@fe.up.pt

Manuel Ricardo
mricardo@inesctec.pt

Ricardo Matos
ricardo.matos@ua.pt

Susana Sargento
ssargento@ua.pt

1 INESC TEC - Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

2 Instituto de Telecomunicações, DETI - University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

3 Instituto de Telecomunicações, Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

Interference is a central problem for wireless networks in general and WMN in particular. Interference is defined as the disturbance caused by a node's RF transmission into neighboring node(s). It degrades the performance of the WMN as having high interference corrupts more packets, increases packet loss ratio (PLR) and packet delay. The amount of interference present in WMN depends on parameters such as the number of nodes, antenna type, routes, transmission power and the number of channels utilized by the network. Achieving satisfactory service quality in WMN using the distributed coordinated function (DCF) of IEEE 802.11 medium access control (MAC) is challenging due to the random access nature of the protocol. Although IEEE 802.11 DCF can well support best effort traffics, it may introduce arbitrarily large PLR, delay and jitter, making it unsuitable for real-time applications with strict quality of service (QoS) requirements. As a result, QoS guarantees cannot be provided to the traffic flows. IEEE 802.11e is an amendment of the IEEE 802.11 standard that defines a set of QoS enhancements through modifications of the MAC layer [9]. IEEE 802.11e is complex to be implemented on legacy IEEE 802.11 networks, as it involves hardware changes to all wireless elements in the network.

In this paper we address the problem of providing a minimal QoS to traffic flows without the need of hardware changes to legacy IEEE 802.11 networks through a new call admission control (CAC) scheme that makes decisions based on interference information. The physical collision constraints, and transmitter-side, receiver-side and when-idle protocol collision prevention constraints are used to design the CAC.

We have considered the WMN consisting of nodes positioned randomly in the network, as shown in Fig. 1, as the basic scenario for our study. The network operates using the basic access scheme of DCF of the IEEE 802.11 MAC protocol known as carrier sense multiple access with collision avoidance (CSMA/CA). The WMN in Fig. 1 is assumed to be owned by a network operator that allows the telecommunication operator's clients (users) to use this network for a price, and in return a minimal QoS guarantee is given to each of the admitted users such as the maximum PLR value (e.g 10 %). A user requests for a virtual link to be established over the WMN. A virtual link is a point-to-point, end-to-end connection between a source and a destination node that could be situated several hops away. Each request is assumed to come one at a time, randomly initiated from any of the nodes in the WMN and destined to another user positioned in any of the other nodes in the WMN. A user is admitted into the network only if the predefined QoS can be provided by the network operator otherwise the request is blocked. The individual links of a virtual link can be placed at different channels. The aim of

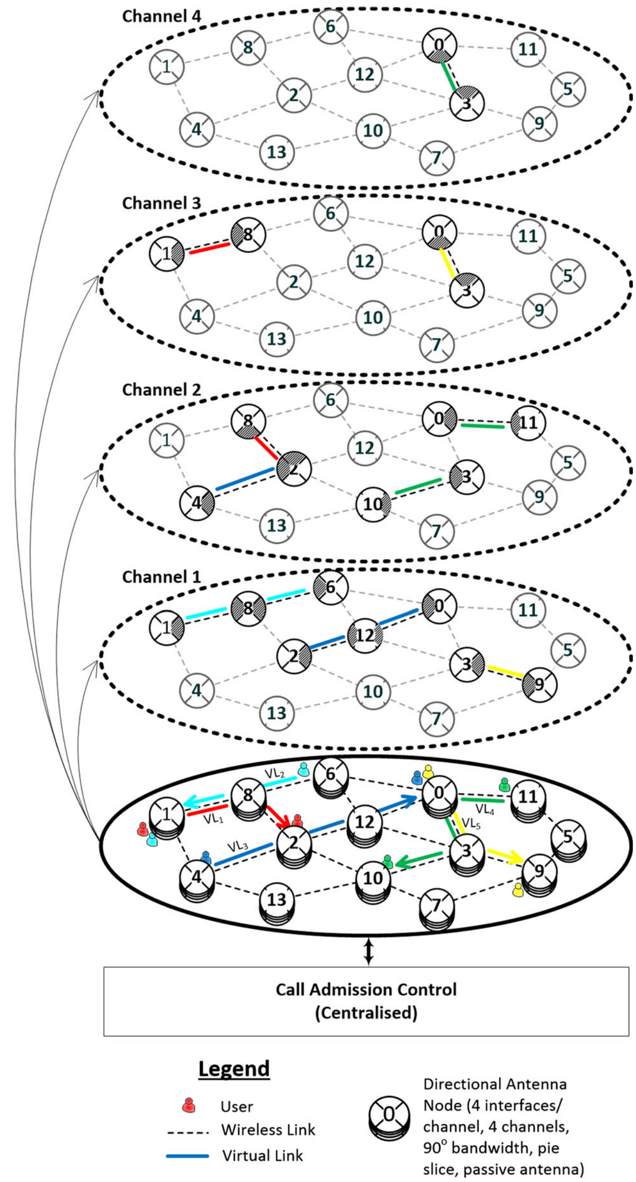


Fig. 1 The wireless mesh network deployed as a basic scenario

the WMN operator is to allow as many users as possible into the network to generate high revenue for him, but without violating the QoS guarantee given earlier either to the newly admitted user or to already admitted users.

This paper provides one major contribution—a centralized CAC for IEEE 802.11 based WMN consisting of nodes using DA. The CAC has two main characteristics: (a) it manages requests from users depending on the available bandwidth in the network; (b) it controls the interference in the WMN whenever a new user is admitted into the network. The requests are managed such that whenever a new user is admitted into the network, radio resources such as interface, bandwidth, transmission power and channel are allocated to the participating nodes. These resources are released once the request has been completed. The interference in the WMN is regulated when a new user is admitted in WMN by controlling the transmission power of all the participating nodes. Our contribution can be particularly useful for network operators to carry out the following activities: (1) to have an automated policing system that is able to guarantee the QoS for its users in terms of PLR; (2) to maximize the number of users that can use the WMN without compromising the QoS requirement; (3) to maximize the revenue from their WMN.

The rest of the paper is organized as follows. In Sect. 2 we present the related works and provide a taxonomy to show the research space of our work. In Sect. 3 we present the power constraints in IEEE 802.11 based WMN. In Sect. 4 we present the proposed CAC. In Sect. 5 we describe the simulation carried out and the results obtained. Finally, in Sect. 6, we draw the conclusions and indicate topics for future work.

2 Related work

In this section we present relevant related works and review the literature from the perspective of CAC for IEEE 802.11 based wireless networks. Figure 2 illustrates a possible taxonomy for CAC where the related works are categorized by the CAC's operation mode, the type of network being controlled, available resource estimation technique, and interference awareness. This taxonomy will be used to describe our research space.

2.1 Centralized CAC

The operation mode of a CAC, centralized or distributed, determines the complexity of its implementation. McGovern et al. [10] proposed a CAC based on the endpoint admission control paradigm, where the endpoint devices probe the network to determine if a call can be supported with acceptable QoS. This scheme achieved a good balance between dynamically loading the network and delivering correct CAC decisions. Abdrabou and Zhuang [11, 12] presented CACs that provide stochastic delay guarantees for IEEE 802.11 ad hoc networks. In [11], the authors characterized the variations of the channel service process using a Markov-modulated Poisson process model. The model was then used to calculate the effective capacity of the IEEE 802.11 channel. The model and the calculated effective capacity was shown could be used effectively to allocate network resources. In [12] the authors predicted and reserved the resources that a new call will consume by using both source traffic and link-layer channel modeling. The simulations demonstrate that the proposed CAC is accurate in the number of admitted flows with good end-to-end delay. Zhao et al. [13] proposed a CAC incorporating load balancing in selecting a path for WMN. Their objective is to increase the number of accepted connections and reduce the connection blocking probability. Their results show that the number of connections in the network and connection blocking probability have been improved using the proposed CAC.

The works by McGovern et al. [10], Abdrabou and Zhuang [11, 12], and Zhao et al. [13], including several

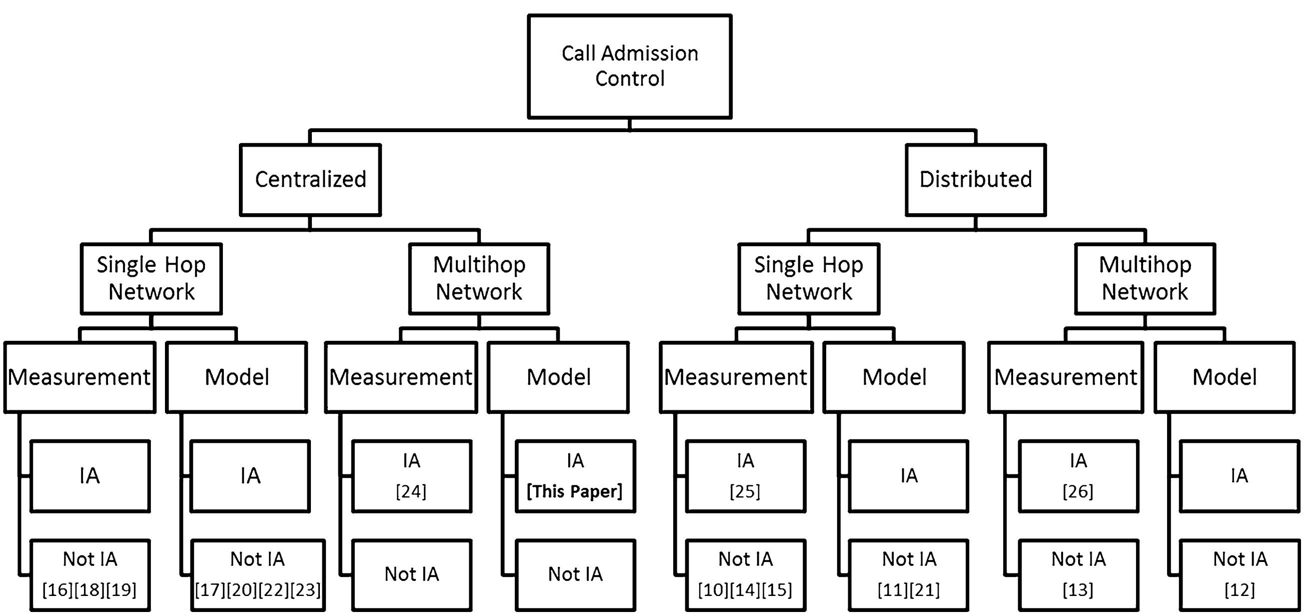


Fig. 2 Taxonomy for call admission control

other recent works [14, 15], have modeled CAC in a distributed approach. Distributed CACs may require specialized stations (STAs) with the implementation of CAC's intelligence; off-the-shelf STAs might not be supported by the network due to lack of compatibility. Furthermore, distributed CACs only have local visibility of the network, providing suboptimal end-to-end QoS guarantee especially for multihop networks. Some of the approaches proposed by the authors exchange control packets to provide the global view to the participating nodes [11, 12], but this does not necessarily achieve the objective due to the presence of hidden nodes in the network. We modeled our CAC using a centralized approach.

2.2 Multi-hop CAC

The type of network being controlled by a CAC affects the performance of a WMN. A CAC for single hop network might not work efficiently for multihop network. Quer et al. [16] addressed the problem of QoS provisioning to VOIP applications in WLAN. The authors proposed a Cognitive Network approach to design a Bayesian network (BN) that is able to make prediction on present and future values of the QoS. Their results show the CAC has better fraction of correct decisions compared with time between idle times (TBIT) admission control scheme. TBIT is simple and effective, enabling every STA to estimate the AP's queuing delay and make independent CAC decisions. Zhao et al. [17] proposed a CAC for homogeneous networks that does admission control quickly without the need for network measurements and complex calculations. The CAC works well for practical sized networks with a finite retransmission limit. Dini et al. [14] proposed a CAC based on channel monitoring and load estimation. The results have demonstrated the proposed CAC is robust and accurate in making CAC decisions.

The works by Quer et al. [16], Zhao et al. [17], and Dini et al. [14], including several other recent works [18–23], have modeled CAC for single hop networks. The CACs may not achieve the same performance for multihop network, since they need to have visibility on end-to-end resource availability. If a CAC performs well in multihop networks, most likely it will perform the same or better in single hop networks. We modeled our CAC for multihop networks.

2.3 Model based CAC

The available resource estimation technique of a CAC can be classified as model based, measurement based or both. Baldo et al. [18] introduced a user-driven CAC that is effective in characterizing the dependence of service quality on the wireless link conditions. Baldo's proposed CAC performed better than other admission control schemes in making a correct admission decision. Yasukawa et al. [15] introduced a CAC that makes decision using the TBIT admission control scheme. Their results revealed that TBIT can be used to make accurate CAC decisions.

The works by Baldo et al. [18], and Yasukawa et al. [15], including several other recent works [10, 13, 14, 16, 19, 24, 25], have modeled CAC based on measurements. This requires continuous monitoring of the network and execution of real time complex algorithms to support requests from users. It would be challenging for end devices which are usually battery powered with limited energy storage to continually monitor the network and make real time measurements to support these CACs. We designed our CAC based on a model that does not require end devices to carry out any measurements.

2.4 Interference aware CAC

Interference awareness is useful when devising a good CAC scheme. Liu and Liao [26] proposed a CAC for estimating the available bandwidth on each associated channel considering inter and intra flow interference. The authors propose a routing metric that strikes a balance between the cost and the bandwidth of the path. This routing metric is used to select an efficient path. The CAC was proven can discover paths that meet the bandwidth requirements of flows and protecting existing flows from QoS violations. Edgar et al. [24] proposed a CAC to regulate the amount of calls in the network to meet the QoS guarantees for the end users. They demonstrated that preserving the WMN under capacity limits, the R-factor metric is able to meet QoS restrictions for VoIP connections. Sridhar and Mun [25] proposed a CAC that considers the sensing state of a radio during the busy and idle periods. These measurements help a node to estimate the position of the interfering nodes and estimate the available resources. The authors shown the CAC performed better in terms of delays and packet losses.

The works by Liu and Liao [26], Edgar et al. [24], and Sridhar and Mun [25] have considered interference modeling in their CAC. Our proposed CAC considers inter and intra flow interference to estimate the resource availability due to the benefit shown in the presented literature.

3 Power constraints for DA in IEEE 802.11 based WMN

A node using DA is able to transmit at different directions at different time slots. In this section we extend the physical collision constraints and protocol collision prevention constraints proposed by Liew in [27] to accommodate DA.

3.1 Physical collision constraints

In a radio link two nodes are within each other's transmission range in order to communicate wirelessly. An active link is a radio link where the nodes actively exchange packets; in a non active link no packets are exchanged. The physical collision constraints can be modeled using the pair-wise interference model among the active links. For a link under the pair-wise interference model, the interferences from the other links are considered one by one. In particular, the pairwise interference model does not take into account the cumulative effects of the interferences from the other links [28].

$$P(a, \theta_b, b) = c(a, \theta_b, b) \cdot P_a^{\theta_b} / r^{\alpha} \quad (1)$$

where $P(a, \theta_b, b)$ is the power received by node b from the direction θ_b of node a, and $P_a^{\theta_b}$ is the power transmitted by node a in the direction of node b as shown in Fig. 3. r is the distance between the two nodes, α is the path-loss exponent, and $c(a, \theta_b, b)$ is a constant in the direction of node b from node a. For instance, for the two-ray ground reflection radio propagation model, α is 4 and $c(a, \theta_b, b)$ is defined as in Eq. 2.

$$c(a, \theta_b, b) = \left(G_a^{\theta_b} \cdot G_b^{((\theta_b + 180^{\circ})\ mod\ 360^{\circ})} \cdot h_a^2 \cdot h_b^2 \right) \quad (2)$$

where $G_a^{\theta_b}$ is the antenna gain of node a in the direction of node b, and $G_b^{((\theta_b + 180^{\circ})\ mod\ 360^{\circ})}$ is the antenna gain of node b in the direction of node a. h_a and h_b are the heights of node a's and node b's antennas respectively. Similar relationship as in Eq. 2 can be derived for other radio propagation models. $\theta_{(.)}$ is suitable to represent any type of DA such as adaptive array antenna, switched beam antenna or several elements of passive DAs connected via multiple interfaces. The present definition is straightforward for adaptive array antenna; in switched beam antenna $\theta_{(.)}$ translates to the *beam id* that radiates in the direction of angle $\theta_{(.)}$; in multi-interface DA system $\theta_{(.)}$ translates to the *interface id* that radiates in the direction of angle $\theta_{(.)}$.

Let us consider two active links, Link 1 and Link 2, communicating using the Basic Access Scheme of IEEE 802.11 MAC protocol (DATA and ACK) with no RTS and CTS. Let T_1 and T_2 be the transmitters and R_1 and R_2 be the receivers at the respective links. T_i and R_i represents the position of a node. DATA is transmitted and ACK is received by T_i, while ACK is transmitted and DATA is received by R_i. We evaluated the cases for both links when each link is transmitting either a DATA packet or an ACK packet. Thus, four different possible combinations of simultaneous transmissions can happen: DATA–DATA, DATA–ACK, ACK–DATA, and ACK–ACK. It also refers a situation when the transmission by different nodes overlap in time. Their transmission may actually be initiated at different time instances so, that the start times of the transmissions are different. The following physical collision constraints can be derived for the four combinations of simultaneous transmissions. When Link 1 and Link 2 each transmit a DATA packet ($DATA_1$–$DATA_2$), a collision occurs at R_2 when,

$$P(T_2, \theta_{R_2}, R_2) < KP(T_1, \theta_{R_2}, R_2) \quad (DATA_1 - DATA_2) \quad (3)$$

where K is the signal to interference ratio (SIR) requirement for a packet to be successfully decoded by the IEEE 802.11 protocol (e.g 10 dB). Independently of T_1 transmitting first or T_2 transmitting first, as long as the two transmissions overlap in time, T_2's DATA transmission will be interfered at R_2 if the constraint in Eq. 3 is satisfied. Similar relationships can be established for the other 3 constraints. The transmission of Link 1 interferes with the transmission of Link 2 ($L_1 \rightarrow L_2$) if,

$$P(R_2, \theta_{T_2}, T_2) < KP(T_1, \theta_{T_2}, T_2) \quad (DATA_1 - ACK_2) \quad (4)$$

$$P(T_2, \theta_{R_2}, R_2) < KP(R_1, \theta_{R_2}, R_2) \quad (ACK_1 - DATA_2) \quad (5)$$

$$P(R_2, \theta_{T_2}, T_2) < KP(R_1, \theta_{T_2}, T_2) \quad (ACK_1 - ACK_2) \quad (6)$$

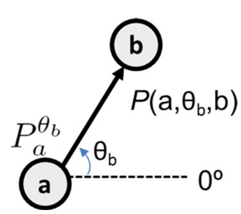


Fig. 3 Transmission power notation for Node a transmitting to Node b using pair-wise interference model

3.2 Protocol collision prevention constraints

The protocol collision prevention constraints of IEEE 802.11 consider the effect of carrier sensing and can be modeled using the pair-wise interference model between active links and radio links. The goal of carrier sensing is to prevent simultaneous transmissions. There are two types of carrier sensing that prevents a transmission:

(a) *Physical carrier sensing (PCS)* The PCS defined by IEEE is the clear channel assessment (CCA) scheme [5]. When a carrier is sensed by the radio interface, the CCA mechanism indicates a busy medium and prevents the radio interface from initiating its own transmission. In this way, an interfering node located within the carrier sensing range (CSRange) of the transmitting node can be detected. The PCS mechanism is triggered every time a packet has to be transmitted by the radio interface.

(b) *Virtual carrier sensing (VCS)* The VCS mechanism uses the information found in IEEE 802.11 packets to determine how long a node has to wait before attempting to transmit. If a node is within the transmission range (TXRange) of a transmitting node, in presence of no other interference, the VCS mechanism is triggered every time a packet is being detected.

Let us consider Link 1 as an active link and Link 2 as a radio link which may or may not be active. If Link 2 is an active link, the prevention of a transmission can occur at the transmitter, receiver or both nodes of Link 2. As a consequence of PCS and VCS, 3 constraints result at the transmitter nodes and another 3 at the receiver nodes.

3.2.1 Transmitter side

A transmitter would refrain from transmitting a DATA packet if it is interfered by another ongoing transmission. Link 1 will interfere with Link 2 ($L_1 \rightarrow L_2$) if,

$$|T_2 - T_1| < CSRange\left(P_{T_1}^{\theta_{T_2}}\right) \quad (\mathrm{DATA}_1 - \mathrm{DATA}_2) \tag{7}$$

$$|T_2 - R_1| < CSRange\left(P_{R_1}^{\theta_{T_2}}\right) \quad (\mathrm{ACK}_1 - \mathrm{DATA}_2) \tag{8}$$

$$|T_2 - T_1| < TXRange\left(P_{T_1}^{\theta_{T_2}}\right) \quad (\mathrm{DATA}_1 - \mathrm{DATA}_2) \tag{9}$$

3.2.2 Receiver side

In the default mode of IEEE 802.11 MAC protocol in commercial products, when T_1 is already transmitting, T_2 can still transmit if T_1 interferes only with R_2 but not T_2. However, R_2 will ignore the DATA from T_2 and not return an ACK to T_2 fearing it may interfere with the ongoing transmission on Link 1 [27]. Link 1 will interfere with Link 2 ($L_1 \rightarrow L_2$) if,

$$|R_2 - T_1| < CSRange\left(P_{T_1}^{\theta_{R_2}}\right) \quad (\mathrm{DATA}_1 - \mathrm{ACK}_2) \tag{10}$$

$$|R_2 - R_1| < CSRange\left(P_{R_1}^{\theta_{R_2}}\right) \quad (\mathrm{ACK}_1 - \mathrm{ACK}_2) \tag{11}$$

$$|R_2 - T_1| < TXRange\left(P_{T_1}^{\theta_{R_2}}\right) \quad (\mathrm{DATA}_1 - \mathrm{ACK}_2) \tag{12}$$

3.2.3 When-idle

If Link 2 is a non active link and A_2 and B_2 are the nodes of this link, the PCS and VCS would still be triggered at any of the idle A_2 or B_2 nodes though it has no packets to send between them.

Link 1 interferes with Link 2 ($L_1 \rightarrow L_2$) if,

$$|A_2 - T_1| < CSRange\left(P_{T_1}^{\theta_{A_2}}\right) \quad (\mathrm{DATA}_1 - \mathrm{A}_2) \tag{13}$$

$$|A_2 - R_1| < CSRange\left(P_{R_1}^{\theta_{A_2}}\right) \quad (\mathrm{ACK}_1 - \mathrm{A}_2) \tag{14}$$

$$|A_2 - T_1| < TXRange\left(P_{T_1}^{\theta_{A_2}}\right) \quad (\mathrm{DATA}_1 - \mathrm{A}_2) \tag{15}$$

$$|B_2 - T_1| < CSRange\left(P_{T_1}^{\theta_{B_2}}\right) \quad (\mathrm{DATA}_1 - \mathrm{B}_2) \tag{16}$$

$$|B_2 - R_1| < CSRange\left(P_{R_1}^{\theta_{B_2}}\right) \quad (\mathrm{ACK}_1 - \mathrm{B}_2) \tag{17}$$

$$|B_2 - T_1| < TXRange\left(P_{T_1}^{\theta_{B_2}}\right) \quad (\mathrm{DATA}_1 - \mathrm{B}_2) \tag{18}$$

4 Call admission control using power interference modeling

The IEEE 802.11 DCF MAC protocol enables nodes to have fair access to the wireless medium, which may prevent the WMN to support the QoS requirements of the services the network cater in particular in the case of medium congestion [16]. A CAC may play a relevant role here to provide QoS by preventing new flows that may keep entering the network even beyond the network's capacity. When the capacity is exceeded, both the existing and the newly admitted flows suffer packet delay, packet loss and low throughput compromising services that must support predefined QoS requirements. In this section the physical collision constraints, and transmitter-side, receiver-side and when-idle protocol collision prevention constraints described in Sect. 3 are used to define a CAC for the WMN.

4.1 Time slot based bandwidth model

The bandwidth in our model is defined by the number of time slots/interface/node/channel/second. For instance for the basic access mode of IEEE 802.11b MAC protocol, the time taken to defer access for a set of DIFS, DATA, SIFS and ACK packets for a pair of nodes constitutes a time slot as shown in Eq. 19. For simplicity the random back off time is not used to define the slot duration although it exists. This time slot is used either to transmit or to receive a data packet, or to refrain from transmitting when a node senses another node transmitting a packet nearby that is not destined to it. There are a total of 1/*time_slot* time slots per second per channel. However, this total time slots will not be considered for provisioning due to the inherent bandwidth wastage from unavoidable packet collisions and backoffs in each channel. As such, a predefined planning threshold value is used (e.g 90 %). This number of available time slots is decremented at the participating node's interface each time a flow is accepted by the CAC to reserve the resources and incremented when the session is completed to release the resources.

$$time\_slot = t_{DIFS} + t_{DATA} + t_{SIFS} + t_{ACK} \quad (19)$$

4.2 CAC overview and channel assignment

Our proposed CAC aims to maintain the QoS of the admitted flows to be below a specific PLR, e.g. 10 %, while maximizing the throughput and the number of flows in the network. The CAC is the network level control that runs whenever there is a request from a user as shown in Algorithm 1. A new request can be either a virtual link establishment (VLE) request or a virtual link release (VLR) request. The CAC first initializes the counter *availableTS* that is responsible to keep track of the amount of available bandwidth in the network. This is done only once during the setup of the WMN.

Algorithm 1 Call Admission Control

```
Require: n ∈ N, newRequest, channels, RadioLinks
availableTS = InitializeTimeSlot()
while newRequest do
    if newRequest==VLE (S_0, D_n, λ) then
        decision = CalculateVLEDecision(S_0, D_n, λ, channels,
        availableTS, RadioLinks)
        if decision==Accept then
            AcceptRequest(VLE)
        else
            RejectRequest(VLE)
        end if
    else if newRequest==VLR(VLid) then
        AcceptRequest(VLR)
    end if
end while
```

A VLE request is triggered by the need for a new virtual link to be established between the source node S_0 and the destination node D_n with a given bandwidth λ, required by the service. Whenever there is a VLE request, the CalculateVLEDecision() procedure is executed to return a *decision*. If the *decision* is to *Accept* the VLE request, then the AcceptRequest() procedure is executed. In the AcceptRequest() procedure the needed time slots are allocated and the appropriate interface, channel and transmit power are assigned to the participating nodes before admitting the VLE request into the WMN. A virtual link's identifier (*VLid*) is designated to identify the accepted VLE request. The unique *VLid* is generated incrementally, so it is the *n*-th flow admitted into the WMN. If the *decision* is to *Reject*, the RejectRequest() will not accept the VLE request and drops the request. A VLR request is triggered by the need to release an already established virtual link identified by its *VLid*. A VLR request is always accepted by the CAC. The time slots used by the request are deallocated and returned to *availableTS*. As long there is an available capacity, new virtual links may be admitted into the WMN and network resources associated to them. Once the capacity usage has reached the predefined threshold, the CAC would refrain from accepting new VLE requests.

The decision to whether accept or not the VLE request is taken in the CalculateVLEDecision() procedure, shown in Algorithm 2. Four steps lead to the decision making: CalculateRoute(), CalculateChannel(), CalculateTPC() and CalculateTS(). CalculateRoute() selects the best multi-hop path between the source and destination of the virtual link. CalculateChannel() assigns the best channel for each hop in the selected route. CalculateTPC() selects the optimal transmission power for all the participating nodes in the network. CalculateTS() determines if there is sufficient bandwidth to accommodate the VLE request.

Algorithm 2 CalculateVLEDecision

```
Require: S_0, D_n, λ, channels, availableTS, RadioLinks
Route = CalculateRoute (S_0, D_n)
Route_c = CalculateChannel(Route, channels, availableTS)
LinksPwr = CalculateTPC (Route_c, RadioLinks)
decision = CalculateTS (LinksPwr, λ, channels,
availableTS, RadioLinks, Route_c)
return decision
```

The CalculateRoute() procedure executes Dijkstra algorithm (shortest path first) which determines the minimum cost path between S_0 and D_n nodes. The procedure returns a route consisting of single hop links as shown in Eq. 20, where (S_n, θ_{D_n}, D_n) is the *n*-th link in the route where S_n forwards the packets it receives to D_n using interface θ_{D_n}, where $D_n = S_{n+1}$.

$$\begin{aligned} Route = {} & (S_0, \theta_{D_0}, D_0) \rightarrow (S_1, \theta_{D_1}, D_1) \rightarrow \ \ldots \ \rightarrow \\ & (S_{n-1}, \theta_{D_{n-1}}, D_{n-1}) \rightarrow (S_n, \theta_{D_n}, D_n) \\ & \forall n; n \geq 0 \end{aligned} \quad (20)$$

As the nodes can operate in more than 1 channel, the CalculatedChannel() procedure, shown in Algorithm 3, assigns each link in the *Route* to operate in a specific channel c from the list of available *channels* given by the network operator. Our CAC selects the channel based on a load balancing strategy and assigns the channel with the highest number of free time slots to each link. The load balancing criterion is guaranteed by the assignment of the least loaded channel when iterating over all links in active routes. This approach is also used in [29]. The CalculatedChannel() procedure returns a route with its associated channel as shown in line 5 of Algorithm 3, where $(S_n, \theta_{D_n}, D_n)_{c_n}$ is the *n*-th link which operates using channel c_n.

Algorithm 3 CalculateChannel ($Route$, $channels$, $availableTS$)

```
Require: Route, channels, availableTS
Ensure: initialTS = ∞
for all links n ∈ Route do
    c_n = c with the highest free time slots
end for

return Route_c = (S_0, θ_{D_0}, D_0)_{c_0} → (S_1, θ_{D_1}, D_1)_{c_1} → … → (S_{n−1}, θ_{D_{n−1}}, D_{n−1})_{c_{n−1}} → (S_n, θ_{D_n}, D_n)_{c_n}
```

4.3 Transmission power control

Adding a new flow into the WMN creates more interference which potentially leads to more packet losses. Our CAC proposes to dynamically assign distinct transmission powers for the participating nodes in the network.

The physical collision constraints, presented in Sect. 3, are used to devise the transmit power control algorithm (TPC).

As the transmission power of the nodes is reduced, the number of : (a) physical collision constraints in the WMN might also reduce. This in turn yield for more feasible VLE connections that meet the QoS requirements to be achieved as the transmission power control also compensates interference; (b) transmitter side, receiver side and when-idle protocol collision prevention constraints in the WMN might also reduce. This may allow for more VLE requests to be accommodated by the WMN due to the increase in capacity because of the transmission power reduction.

The proposed TPC has two main properties that are an extension of the properties I and II of decoupled adaptive power control proposed in [27] to accommodate DA.

4.3.1 *Property 1: use the minimum transmission power sufficient to maintain link connectivity*

Transmitter T_i uses the interface θ_{R_i} to transmit to the interface θ_{T_i} of receiver R_i and vice versa. The minimum transmit power of T_i and R_i given by Eqs. 21 and 22 respectively, which assures that the reduced power satisfies the minimum received power threshold required to maintain the link's connectivity. RX_{th} is the received signal strength threshold to decode a packet.

$$\left(P_{T_i}^{\theta_{R_i}}\right)_{min} = \frac{P_{T_i}^{\theta_{R_i}}}{P(T_i, \theta_{R_i}, R_i)} \times RX_{th} \tag{21}$$

$$\left(P_{R_i}^{\theta_{T_i}}\right)_{min} = \frac{P_{R_i}^{\theta_{T_i}}}{P(R_i, \theta_{T_i}, T_i)} \times RX_{th} \tag{22}$$

4.3.2 *Property 2: avoid creation of new physical collision constraints during transmit power control*

When a transmitter reduces its transmission power, the signal to noise ratio gets weaker at the receiver. Therefore, new physical collision constraints could emerge interfering the communication of the link if any of the constraints in Eqs. 3–6 are satisfied. A node needs to consider the interference from its surrounding links when adjusting its transmit power. Let N_{T_i} and N_{R_i} be the sets of neighboring nodes that are not interfering with T_i and R_i respectively, but may do so if the power of T_i and R_i are reduced too drastically. We assume that the power of the nodes in N_{T_i} and N_{R_i} do not change when calculating the new power for T_i and R_i. We require,

$$(P_{T_i}^{\theta_{R_i}})_{adj} \geq \frac{KP(n, \theta_{R_i}, R_i)P_{T_i}^{\theta_{R_i}}}{P(T_i, \theta_{R_i}, R_i)}, \quad \forall n \in N_{R_i} \tag{23}$$

$$(P_{R_i}^{\theta_{T_i}})_{adj} \geq \frac{KP(n, \theta_{T_i}, T_i)P_{R_i}^{\theta_{T_i}}}{P(R_i, \theta_{T_i}, T_i)}, \quad \forall n \in N_{T_i} \tag{24}$$

In general, N_{T_i} and N_{R_i} do not need to cover all nodes in the network. Only nodes n that satisfy the following condition need to be considered:

$$n \in N_{T_i} \iff P(n, \theta_{T_i}, T_i) \geq RX_{th}/K$$
$$n \in N_{R_i} \iff P(n, \theta_{R_i}, R_i) \geq RX_{th}/K$$

4.3.3 *Transmit power control algorithm*

The CalculateTPC() procedure in Algorithm 4, executes the TPC algorithm. For each link in the *RelevantLinks* set, CalculateTPC() returns the list, *LinksPwr*, of the transmission power adjusted to minimize interference whenever a VLE request is received. The relevant links in *RelevantLinks*, either belong to the current *Active Links* set or to the route $Route_c$ of the virtual link being established. The new transmission power of the participating interfaces are calculated in lines 2 and 3 of Algorithm 4 using Eqs. 21–24.

The maximum value between Property 1 and 2 is considered to be the new transmission power as it fulfills both the condition of the properties, which are then stored in the *LinksPwr* list. The power in the *LinksPwr* are assigned to the participating interfaces of the nodes in case of the VLE request acceptance.

Algorithm 4 CalculateTPC ($Route_c, RadioLinks$)

Require: $Route_c, ActiveLinks \in RadioLinks$
Ensure: $RelevantLinks = Route_c \cup ActiveLinks$
Ensure: $LinksPwr = \{\}$
for all $(S_n, \theta_{D_n}, D_n)_{c_n} \in RelevantLinks$ **do**
  $\left(P_{S_n}^{\theta_{D_n}}\right)_{new} = \max\left[(P_{T_i}^{\theta_{R_i}})_{min}, (P_{T_i}^{\theta_{R_i}})_{adj}\right]$
  $\left(P_{D_n}^{\theta_{S_n}}\right)_{new} = \max\left[(P_{R_i}^{\theta_{T_i}})_{min}, (P_{R_i}^{\theta_{T_i}})_{adj}\right]$
  $LinksPwr.add(\left(P_{S_n}^{\theta_{D_n}}\right)_{new}, \left(P_{D_n}^{\theta_{S_n}}\right)_{new})$
end for

return $LinksPwr$

4.4 Bandwidth reservation

Bandwidth reservation in the CAC is done via CalculateTS() procedure shown in Algorithm 5. The procedure receives: (1) the proposed power to be assigned to links if a VLE request is accepted, *LinksPwr*; (2) the required bandwidth for the VLE request, λ; (3) the list of channels given by the network operator, *channels*; (4) the currently available time slots, *availableTS*; (5) the set of radio links consisting of active and non active links, *RadioLinks*; and (6) the route by channel connecting S_0 and D_n nodes for a VLE request, $Route_c$.

A temporary counter *tempTS* is initialized every time the CalculateTS() procedure is called. This is because some of the bandwidth may be freed due to compaction with the proposed transmit power reduction from the CalculateTPC() procedure. The *tempTS* counter is used to evaluate the opportunity to accept the VLE request after adopting the proposed transmission power using the assigned channels in $Route_c$.

Algorithm 5 CalculateTS ($LinksPwr$, λ, $channels$, $availableTS$, $RadioLinks$, $Route_c$)

Require: $LinksPwr, \lambda, channels, availableTS, RadioLinks, Route_c$

$tempTS = InitializeTimeSlot()$
for all $c \in channels$ **do**
  for all $L_1 \in (ActiveLinks_c \in RadioLinks_c) \cup (Links_c \in Route_c)$ **do**
    $tempTS[c][T_1][\theta_{R_1}] -= \lambda$
    $tempTS[c][R_1][\theta_{T_1}] -= \lambda$
    for all $L_2 \in RadioLinks_c$ **do**
      if $L_2 \in (ActiveLinks_c \in RadioLinks_c) \cup (Links_c \in Route_c)$ **then**
        if $(L_1 \rightarrow L_2)_{Eq.7-Eq.9}$ **then**
          $tempTS[c][T_2][\theta_{R_2}] -= \lambda$
        else if $(L_1 \rightarrow L_2)_{Eq.10-Eq.12}$ **then**
          $tempTS[c][R_2][\theta_{T_2}] -= \lambda$
        end if
      else if $L_2 \in (nonActiveLinks_c \in RadioLinks_c)$ **then**
        if $(L_1 \rightarrow L_2)_{Eq.13-Eq.15}$ **then**
          $tempTS[c][A_2][\theta_{B_2}] -= \lambda$
        else if $(L_1 \rightarrow L_2)_{Eq.16-Eq.18}$ **then**
          $tempTS[c][B_2][\theta_{A_2}] -= \lambda$
        end if
      end if
    end for
  end for
end for
Ensure: decision = Accept
for all $channel \in tempTS.keys()$ **do**
  for all $node \in tempTS[channel].keys()$ **do**
    for all $interface \in tempTS[channel][node].keys()$ **do**
      if $tempTS[channel][node][interface] < 0$ **then**
        $decision$ = Reject
      end if
    end for
  end for
end for
if $decision == Accept$ **then**
  $availableTS = tempTS$
end if

return $decision$

The transmitter-side, receiver-side and when-idle protocol collision prevention constraints are used to manage the shared capacity of the WMN by evaluating all active links in the network and links in the proposed route, against all the radio links present in the network. For each active link and link in $Route_c$, denoted as L_1 (T_1, θ_{R_1}, R_1), the procedure decrements by the time slots by λ at (T_1, θ_{R_1}) and (R_1, θ_{T_1}) interfaces. If L_2 is an active link (T_2, θ_{R_2}, R_2), the time slots are decremented by λ at the following interfaces:

(a) (T_2, θ_{R_2}) if any constraints in Eq. 7–9 is satisfied;
(b) (R_2, θ_{T_2}) if any constraints in Eq. 10–12 is satisfied.

If L_2 is not an active link (A_2, θ_{B_2}, B_2), the time slots are decremented at the following interfaces:

(a) (A_2, θ_{B_2}) if any constraints in Eq. 13–15 is satisfied;
(b) (B_2, θ_{A_2}) if any constraints in Eq. 16–18 is satisfied.

Finally the *tempTS* counter is verified if it remains positive after the decremental process above. If yes, it indicates that there is sufficient bandwidth to support the VLE request. The VLE request will be proposed to be accepted and the *tempTS* value is saved to *availableTS* counter to keep record of the final time slot status of the WMN. Otherwise, the decision is to reject, indicating insufficient bandwidth to accommodate the VLE request. In this case, the proposed route, channel and transmit powers are disregarded. A new route is not calculated by the CAC though there might be possible that a longer route has sufficient resources available to accommodate the request. Additional hops would incur more delay and congest the network due to higher inter and intra flow interferences. The CalculateTS() procedure returns the *decision* as the output.

5 Performance evaluation

This section evaluates the performance of the CAC by means of simulation using network simulator 2 (ns-2). Each of the phases of the CAC, the TPC and the bandwidth reservation, were evaluated separately to assess the contribution of each phase to the global benefit. The impact of using DA or OA antennas as well as using single or multiple channels was also evaluated. We show that the proposed CAC is able to provide the PLR guarantees for WMNs that use DA or OA.

5.1 Directional antenna in ns-2

Ns-2 was improved to support nodes with DA. Each node is assumed to have 4 interfaces per channel, where each interface is connected with an element of 90° passive DA of gain 2 with respect to the gain of an isotropic antenna. Each interface has its own MAC, NAV, interface queue (IFQ), and maintains its own ARP table. The DA in interfaces 0, 1, 2 and 3 are pointed respectively to angles 0°, 90°, 180°, and 270°.

5.2 Simulation setup

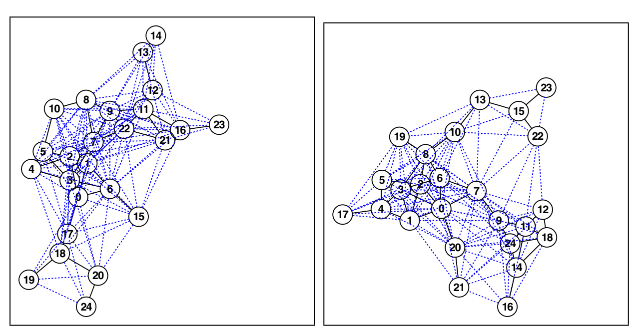
We defined a topology where 25 nodes are placed randomly in 1500 m × 1500 m area. Each user's request is assumed to come one at a time, to be point-to-point and randomly initiated from any of the nodes aiming to reach another user positioned at any other remaining nodes in the network, replicating the scenario in Fig. 1. All nodes are static and the routes are configured statically based on the route proposed by the CAC for all admitted flows. 10 random topologies were simulated, where each topology is repeated 3 times with different seeds. Some examples of the random topologies used in the simulation are shown in Fig. 4 when OA is used; the solid and the dashed lines represent nodes within receiving and carrier sensing range respectively. The rest of the parameters used in the simulation are presented in Table 1.

For simplicity and in order to evaluate our contributions, we assume a shared capacity of 11 Mbit/s/channel and, per Eq. 19 and Table 1, a time slot with a period of 1686.182μs is obtained. Hence there are approximately 593 time slot/s/channel. A predefined planning threshold value of 90 % is used, that is, we consider 533 time slot/s/channel.

5.3 Methodology

The CAC is evaluated following the below 5 steps to gauge the gain of its each component.

(a) Setup 0: OA/DA, 1 Channel, No TPC, No Bandwidth Reservation—This is a setup for the purpose of benchmarking. It considers the default settings of ns-2, where WMNs are tested using OA and DA. All nodes operate using single channel without TPC and bandwidth reservation mechanisms of the proposed CAC;



(a) **(b)**

Fig. 4 Example of random topologies for network with nodes using OA. **a** Random topology 1. **b** Random topology 2

Table 1 Parameter settings used in ns-2.33 simulations

Parameter	Setting
Simulation time	180 s
Simulation runs	30 (10 topologies × 3 seeds)
Number of nodes	25
Load per request	252 kbps or 21 pkt/s
Traffic	UDP; Poisson process
Packet size	1500 bytes
IFQ length	50 packets
SIR	10 dB
Propagation	2-Ray ground reflection
Default transmit power	281.84 mW
RXThresh; CSThresh	36.5 nW; 156 nW
Frequency	2.4 GHz; 4 channels
Type of antenna	OA, DA
DA angles	0°, 90°, 180°, 270°
Number of DA/node	4, 90° beamwidth each
Antenna gain	OA:1, DA:2 (in ref. to an isotropic antenna)
MAC	IEEE 802.11b
Access mode	Basic (DATA, ACK)
Data rate; basic rate	11 Mbps; 1 Mbps
t_{DIFS}; t_{SIFS}; t_{ACK}	50 µs; 10 µs; 304 µs
t_{DATA} (1500+78)bytes	1322.182 µs

(b) Setup 1: OA/DA, 1 Channel, TPC, No Bandwidth Reservation—This setup considers Setup 1 with only the TPC mechanism of the proposed CAC:

(c) Setup 2: OA/DA, 1 Channel, No TPC, Bandwidth Reservation—This setup considers Setup 1 with only the bandwidth reservation mechanism of the proposed CAC;

(d) Setup 3: OA/DA, 1 Channel, TPC, Bandwidth Reservation—This setup considers Setup 1 with the TPC and bandwidth reservation mechanisms of the proposed CAC;

(e) Setup 4: OA/DA, 4 Channels, TPC, Bandwidth Reservation—Finally, in this setup we consider Setup 3, but the CAC considers multichannel.

The results for PLR, rate of success (RS), throughput per flow, and aggregated throughput of the WMN are shown in Fig. 5. The graphs on the left column represent WMNs with nodes using OA, and the ones on the right represent WMNs with nodes using DA. Lines with square, inverted triangle, diamond, circle and triangle symbols are used to represent Setup 0–4, respectively.

PLR is the percentage of the total number of packets unsuccessful to be delivered over the total number of packets sent. It is calculated using Eq. 25. RS is the fraction of the VLE request attempts that were accepted in percentage as shown in Eq. 26. Throughput per flow is measured as the total number of packets successfully received at a flow's destination times the packet size over the duration of the flow. Formally, the throughput is defined by Eq. 27, where T_D is the duration of the flow. Aggregated throughput is measured as the total number of packets successfully received at the destinations times the packet size over the duration of the flows in the WMN. It is calculated using Eq. 28, where n is the number of flows, i is the flow number and T_{D_i} is the duration of flow i.

$$PLR = \frac{(Total\ Pkts\ Sent - Total\ Pkts\ Rcvd)}{Total\ Pkts\ Sent} \times 100 \quad (25)$$

$$RS = \frac{Tot.\ VLE\ Req.\ Accepted}{Tot.\ VLE\ Req.\ Attempt} \times 100 \quad (26)$$

$$Tput/flow = \frac{RcvdPkts \times Packet_{Size}}{T_D} \quad (27)$$

$$AggTput = \sum_{i=1}^{n} \frac{RcvdPkts_i \times Packet_{Size_i}}{T_{D_i}} \quad (28)$$

5.4 Transmit power control

To evaluate the gain of TPC, results from Setup 0 are compared with Setup 1, represented in Fig. 5. Setup 0 represents the default mode of WMN operation without any QoS provisioning. In Setup 1, the TPC component of the CAC is implemented. The objective of TPC is to reduce

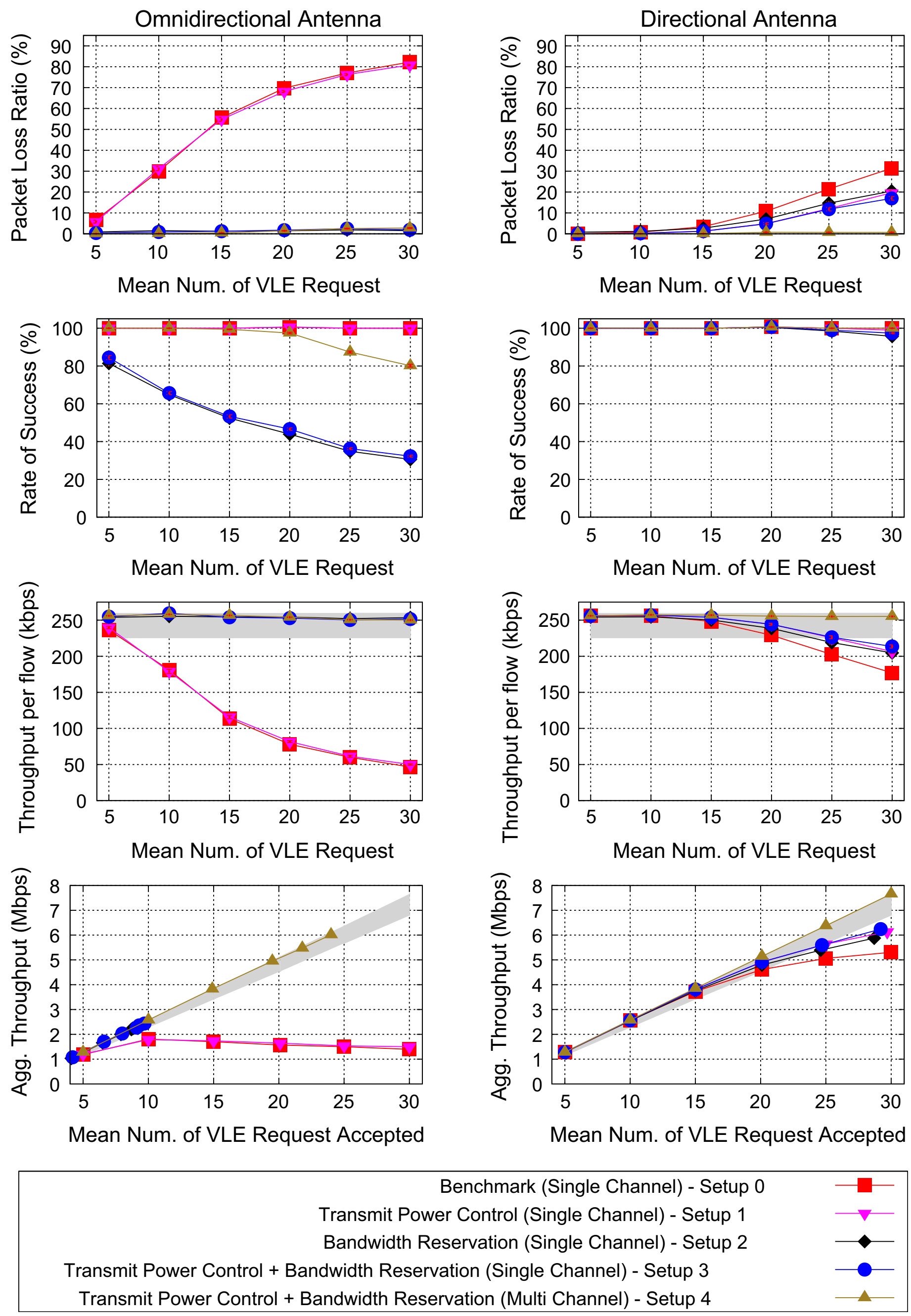


Fig. 5 Simulations results

the interference in the WMN by controlling the transmission power of the participating nodes.

(a) *Packet loss ratio* The values of PLR increase for DA as the mean number of VLE requests increase for both Setup 0 and Setup 1, with Setup 1 presenting a slower PLR increase. On the other hand, TPC has no significant gain when used in OA. This is because DA is able to transmit at desired directions and reduce interference on unwanted directions. The PLR exceeds 10 % when the VLE requests go beyond 19 and 23 in Setup 0 and Setup 1, respectively in DA. Hence, Setup 1 achieves an additional gain of 20 % VLE requests operating within the required QoS. The TPC component available in Setup 1 is able to adjust the node's transmission power judiciously to reduce PLR due to collisions and carrier sensing. It also encourages for more VLE requests to operate within the QoS threshold. In summary, the TPC component of the CAC is attractive for DA in assisting to reduce the PLR. However, the TPC component alone is unable to maintain the PLR value lower than 10 %, especially for the large mean number of VLE requests.

(b) *Rate of success* The RS for DA is always 100 % for Setup 1, since it does not stop the VLE requests from being accepted in the WMN. This is the same for the case of OA. This is the major reason contributing to the high PLR, as all VLE requests are kept on being admitted into the WMN despite the fact that the network is unable to provide the needed QoS.

(c) *Throughput per flow* In both Setup 0 and Setup 1 the throughput per flow decreases for DA with the increase of VLE requests. The throughput in Setup 1 is higher than the one in Setup 0, especially for the cases of large VLE requests. In the case of 30 VLE requests, the per flow throughput is 177 and 207 kbps in Setup 0 and Setup 1, respectively. Hence, Setup 1 is able to cater about 16 % more traffic than Setup 0. The shaded area in the graph represents the PLR < 10% region. When the mean number of VLE requests goes beyond 21 and 25 requests in Setup 0 and Setup 1, respectively, the throughput per flow is above 10 % PLR . TPC allows for more VLE requests to operate within the required QoS (20 % in this case). For the case of OA, the TPC has no significant gain: accepting all VLE requests into the WMN, higher than its operating capacity congests the network. Though TPC assists to reduce potential collision by increasing the SINR of the links, this does not completely eliminate the collision in the network. As a consequence, the throughput per flow is reduced when the VLE requests increase.

(d) *Aggregated throughput* As the mean number of admitted VLE requests increase, DA's aggregated throughput increases in Setup 0 and Setup 1. The throughput values in Setup 1 is higher than the one in Setup 0 when the VLE requests increase beyond 15. The shaded area in the graph represents the PLR < 10 % region. Setup 1 is able to handle 25 % more VLE requests than Setup 0 while operating within the predefined QoS guarantee. TPC is not attractive for OA, since it is unable to operate within 10 % PLR region for all mean number of VLE requests accepted. DA has higher network capacity as it can allow for more parallel communications to be initiated, hence it is able to transport more network throughput than OA. Comparing Setup 0 and Setup 1, TPC is attractive for DA, since it transports more aggregated throughput within the QoS guarantee, whereas for OA both setups performed similarly.

(e) *Discussion* The TPC properties assist DA to better manage the resources i.e transmission power of the nodes, which have resulted in reduced collisions, exponential back offs and retransmissions. Setup 1 has lower PLR, higher aggregated and per flow throughput with 100 % RS compared with Setup 0. Nevertheless, it is insufficient to maintain PLR < 10 %, which is, in this case, the objective of the CAC. A traffic policing mechanism, such as a bandwidth reservation scheme, which can limit the number of VLE requests admitted into the WMN would be beneficial to achieve PLR < 10 %.

5.5 Bandwidth reservation

To evaluate the gain of bandwidth reservation, results from Setup 0 are compared with results from Setup 2, represented in Fig. 5. In Setup 2, the bandwidth reservation component of the CAC is implemented. The bandwidth reservation is aimed to assist to manage the available bandwidth in the WMN and control the number of VLE requests accepted into the WMN, so that the guaranteed QoS is not violated.

(a) *Packet loss ratio* In Setup 0 and Setup 2 with DA, the values of PLR increase as the mean number of VLE requests increase. In the case of OA, though the PLR does increase for Setup 0, the bandwidth reservation mechanism in Setup 2 is able to contain its PLR to be below 10 %. This is not the case for DA: despite having lower PLR value than Setup 0, Setup 2 has more than 10 % PLR when the VLE Requests increase beyond 22. This is because DA has higher degree of hidden node (HN) when compared to OA: more HN are created with more flows admitted into the WMN; though the provisioning is done well at model level, at simulation level more collisions are induced due to HN and this contributes to a larger PLR value. We can conclude that the bandwidth reservation component of the CAC is useful in maintaining the QoS guarantee in OA and DA, but it is still not sufficient.

(b) *Rate of success* The RS in Setup 2 does not reduce significantly, due to the higher capacity of WMN with DA to transport more traffic in the network. In the case of OA, the RS in Setup 2 has dropped significantly when the VLE requests increase: the bandwidth reservation component has reduced the amount of VLE requests accepted in the WMN. This shows an effective mean to manage the resources providing the needed QoS guarantee, since the PLR values are kept <10 % .

(c) *Throughput per flow* As the VLE requests increase, throughput decreases in DA in both setups: although DA has higher network capacity, the HN affected the throughput especially on the higher value of mean number of VLE requests. The bandwidth reservation mechanism in Setup 2 has improved the throughput performance compared with Setup 0. For the case of OA, Setup 2 always has a large per flow throughput within the 10 % PLR value, due to the bandwidth reservation mechanism and lower degree of HN.

(d) *Aggregated throughput* DA achieves higher aggregated throughput compared with OA. This is because WMN with DA has higher network capacity due to the fact that the bandwidth reservation mechanism allows for more VLE requests to be admitted. OA is able to admit only 9 VLE requests, while DA manages to admit 22 VLE requests within the QoS threshold. We can conclude that bandwidth reservation in DA is effective to assist a WMN to operate within its QoS guarantee and allows for more VLE requests to be admitted.

(e) *Discussion* The bandwidth reservation property assists DA to manage the resources well, with decreasing collisions, exponential back offs and retransmissions. Setup 2 has lower PLR and RS, higher aggregated and per flow throughput compared to Setup 0. Bandwidth reservation alone is clearly insufficient to maintain PLR < 10 %. TPC with bandwidth reservation would be advantageous to achieve this restriction.

5.6 TPC with bandwidth reservation

Setup 3 represents a fully functional CAC that has the bandwidth reservation and TPC components being implemented. The CAC is aimed to assist: (a) to manage the available bandwidth in the WMN and control the number of accepted VLE requests, so that the guaranteed QoS is not violated; (b) to reduce the interference in the WMN by controlling the transmission power of the participating nodes.

(a) *Packet loss ratio* The values of PLR increase as the mean number of VLE requests increase in DA. Setup 3 has lower PLR values compared with Setup 0, when considering more than 15 VLE requests. DA has relatively higher PLR values compared with OA especially when the VLE requests increase. For the case of 30 VLE requests, the PLR in OA decreased by 89 % compared with DA in Setup 3. With the bandwidth reservation and TPC components of CAC, OA is able to maintain its PLR below 10 %, but for DA it is insufficient to maintain the QoS guarantee due to the higher degree of HN. Though the provisioning is done well at model level, at simulation level more collisions are induced due to HN and this contributes for the higher PLR values. We can conclude that the CAC is useful in improving the QoS guarantee for OA and for DA. In the case of DA though it is insufficient to maintain the needed QoS guarantee, it reduces the PLR of the WMN by 46 % compared with Setup 0 for 30 VLE requests.

(b) *Rate of success* The RS in DA is around 100 % when the VLE requests increase. For the case of 30 VLE requests, the RS is approximately 32 % in OA and 97 % in DA. This is expected in OA, since the bandwidth reservation component has managed to achieve the needed QoS guarantee by controlling the number of VLE requests in the WMN; however, the success rate is very low. DA has a much better RS than OA because of the increased network capacity. Nevertheless, the effect of HN at a large number of admitted requests makes the CAC not able to maintain the QoS guarantee beyond 21 requests. Comparing Setup 0 with Setup 3, Setup 3 has a lower RS than Setup 0 in OA and similar RS in DA. This is expected since the CAC has reduced the amount of admitted VLE requests, but DA has more capacity and it is able to admit more VLE requests.

(c) *Throughput per flow* The throughput in DA decreases when the mean number of VLE requests increase. This is again due to the higher degree of HN in DA. In the case of 30 VLE requests, the per flow throughput in OA is approximately 252 and 214 kbps in DA. Comparing Setup 0 with Setup 3, Setup 3 has higher throughput per flow due to the reduced retransmissions and collisions.

(d) *Aggregated throughput* As the mean number of admitted VLE requests increase, throughput increases in DA. OA is able to admit 9 VLE requests while DA admits 24 VLE requests within WMN's QoS guarantee. Comparing Setup 0 with Setup 3, Setup 3 accommodates less users; nevertheless, it presents a larger aggregated throughput within the QoS guarantee for both types of antennas.

(e) *Discussion* The CAC with the bandwidth reservation and TPC components are able to efficiently manage the resources with reduced collisions, exponential back offs and retransmissions. Setup 3 has the lowest PLR, highest aggregated and per flow throughput with 100 % RS compared with Setup 0. Since the CAC has no visibility of the HN, it increases the PLR in DA, especially on the high loads of VLE requests.

5.7 Multi channel

To evaluate the gain of CAC with MC component, results from Setup 3 are compared with Setup 4. Setup 4 represents a CAC which is able to manage WMN's radio resources and control transmit power of the nodes intelligently in the multi channel environment.

(a) *Packet loss ratio* The values of PLR in DA in Setup 4 are constant and below 10 % when the mean number of VLE requests increase. Although DA has higher degree of HN, it did not affect the performance of the CAC, since the available resources and inherent interference are able to be managed well in the network. Comparing Setup 3 with Setup 4, the PLR values in DA have decreased drastically whereas the performance of PLR for OA is similar. For the case of 30 mean number of VLE requests, the PLR in DA has decreased by approximately 96 % . We can conclude that the CAC with MC has the highest gain in DA, maintaining the QoS guarantees.

(b) *Rate of success* In MC, bandwidth reservation is expected to control the number of user requests admitted, but DA did not face this issue, since the higher capacity in the WMN using DA allows for more VLE requests to be admitted. On the other hand, MC did not help for OA, since RS reduces significantly: only 80 % of the VLE requests are admitted when the load is 30 VLE requests.

(c) *Throughput per flow* In Setup 4 the throughput in DA is constant when the mean number of VLE requests increase. For the case of 30 VLE requests, the per flow throughput in DA is approximately 252 kbps and all are within 10 % PLR. Comparing Setup 3 with Setup 4, Setup 4 has higher throughput per flow for DA. In OA it has similar performance for all the mean number of VLE requests. We can conclude that the CAC with MC has the highest gain in DA, while maintaining the QoS guarantees.

(d) *Aggregated throughput* As the mean number of admitted VLE requests increase, throughput also increases in DA. The MC allowed all the traffic to be transported with the QoS guarantees for the admitted VLE requests. OA is able to admit 24 VLE requests while DA is able to admit 30 VLE requests, which represents an increase of 25 % more VLE requests. Comparing Setup 4 and Setup 3, the aggregated throughput of Setup 4 is higher and it accommodates higher mean number of users.

(e) *Discussion* Setup 4 has lower PLR, higher aggregated and per flow throughput with 100 % RS compared with Setup 0. Multi channel CAC with bandwidth reservation and TPC properties with DA are able to efficiently manage the resources and maintain the PLR below 10 %.

6 Conclusion

Interference is a fundamental issue in WMNs and it affects the performance of a network. In this paper we have characterized the power interference in IEEE 802.11 CSMA/CA based WMN using DA. A model based centralized CAC has been proposed for the network using the physical collision constraints, and transmitter-side, receiver-side and when-idle protocol collision prevention constraints. The proposed CAC manages the acceptance of VLE requests depending on the available bandwidth in the network. Whenever a VLE request is admitted into the network, radio resources such as interface, bandwidth, transmission power and channel are allocated to the participating nodes and deallocated once the request has been completed. The CAC is also able to contain the interference in the WMN by controlling the transmission power of nodes. The CAC can be used not only in WMNs with nodes using DA, but also with nodes using OA despite having non-homogeneous wireless channel capacity.

The proposed CAC is able to keep the PLR of the admitted requests below the specified QoS. However, the HN in WMNs does affect the performance of CAC. Physical and protocol constraints from the power interference modeling could also be used to design a scheduling mechanism to assist to alleviate the amount of HN in the network. Further in this work, the shortest path was chosen as the route from a source node to its destination node; if no resources are available in this shortest path, the request will not be accepted. If there is no shortest path, a least interfered path closest to the shortest path's hop could be also chosen if resources are available. This would allow for more user requests to be admitted and generate bigger revenue to the network operator. In our work, the CAC increases the number of active VLE requests in the WMN subject to PLR as the QoS requirement. Fairness will be studied to analyze if the CAC maintains the fairness provided by IEEE 802.11 DCF MAC protocol. All these aspects will be addressed in the future work.

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Saravanan Kandasamy received the B.Eng. (2000) in Electronics majoring in Computer from Multimedia University, Malaysia and M.Sc. (2004) in Communications and Network Engineering from University Putra Malaysia. He is currently a researcher in the Centre for Telecommunications and Multimedia of INESC TEC (www.inesctec.pt) and pursuing Ph.D. in the MAP Doctoral Programme (www.tele.map.edu.pt). His research interest include directional antenna, radio resource management, transmission power control and statistical modeling for IEEE 802.11 based wireless networks.

Carlos Marques concluded in July 2010 his Integrated M.Sc. in Electronics and Telecommunications Engineering from the Department of Electronics, Telecommunications and Informatics of University of Aveiro. From 2010 to 2013 he has joined Institute of Telecommunications, located in University of Aveiro Campus, as a researcher. He has been involved in some national projects, such as, Panorama and others in collaboration with PT Inovação, and European ones, such as Euro-NF. In 2013 he has joined PT Inovação, located in Aveiro, and from them, he has been working on 3GPP and cloud networking. He has been involved in some European projects, such as MCN. His research interests are related with simulation platforms, wireless mesh networks, context-awareness, cloud networking and 3GPP.

Tania Calçada received a Licenciatura (1999) and the Ph.D. (2013) degree in Electrical and Computer Engineering from Porto University. Her Ph.D. topic was Channel assignment strategies for wireless mesh networks. Between 1999 and 2003 she was working for Novis, a telecom operator, designing corporate network solutions. In the next 10 years she did research at INESC TEC in the area of wireless networks involved in projects related with wireless mesh networks and vehicular networks. During 2013 she taught Network Engineering and Wireless Telecommunication Systems at ESTGL. Currently, Dr. Tania Calçada is a associate researcher at Faculdade de Engenharia da Universidade do Porto in the Centre of Competence in Future Cities.

Manuel Ricardo received his Ph.D. degree in 2000 in Electrical and Computer Engineering from Porto University. Currently he is an associate professor at the Faculty of Engineering of University of Porto, where he gives courses in mobile communications and computer networks. He coordinates Centre for Telecommunications and Multimedia of INESC TEC (www.inesctec.pt).

Ricardo Matos received his Ph.D. in Electrical Engineering by the University of Aveiro in January 2013. He is a member of Instituto de Telecomunicações since September 2008, belonging to the Network Architectures and Protocols (NAP) group (http://nap.av.it.pt). In January 2013, he joined a vehicular networking company, Veniam'Works, which builds a seamless low-cost vehicle-based internet infrastructure. He has been involved in several national projects, as well as in the FP6 European Project WEIRD, and FP7 European Project Euro-NF. His current research interests are related with vehicular networking, M2M communications, future Internet, virtualization techniques, wireless mesh networking, self-management, and context-awareness.

Susana Sargento received her Ph.D. in 2003 in Electrical Engineering in the University of Aveiro (with a 7 months stay in Rice University in 2000 and 2001). She joined the Department of Computer Science of the University of Porto in September 2002, and is an Associate Professor in the University of Aveiro and the Institute of Telecommunications, where she is leading the Network Architectures and Protocols (NAP) group (http://nap.av.it.pt). She was a Guest Faculty of the Department of Electrical and Computer Engineering from Carnegie Mellon University, USA, in August 2008, where she performed Faculty Exchange in 2010/2011. In March 2012, Susana has co-founded a vehicular networking company, Veniam'Works, which builds a seamless low-cost vehicle-based internet infrastructure. Susana has been involved in several national and international projects, taking leadership of several activities in the projects, such as the network of vehicles on buses and trucks, as well as several fixed stations, counting with more than

600 vehicles in the city of Porto, Portugal. She has been TPC-Chair and organizing several international conferences, has also been a reviewer of numerous international conferences and journals, such as IEEE Wireless Communications, IEEE Networks, IEEE Communications. Her main research interests are in the areas of Next Generation and Future Networks, more specifically QoS, routing, mobility, self- and cognitive networks. She regularly acts as an Expert for European Research Programmes.