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Analyse Formelle des Protocoles de Communication des Réseaux de Capteurs sans Fil Corporels

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Résumé

Cette thèse porte sur l'évaluation des performances des protocoles de contrôle d'accès au support (MAC) pour le réseau de capteurs corporel sans fil (WBAN) par le biais des méthodes de la vérification formelle. L'importance des WBAN a incité les chercheurs à proposer de nouveaux protocoles MAC afin de satisfaire les exigences des WBAN, ce qui nous a conduits à élaborer, dans un premier travail, une analyse comparative, quantitative et qualitative, des protocoles MAC existants pour les WBAN. Selon nos résultats de comparaison, le protocole MAC de la norme IEEE 802.15.6 prend en compte la majorité des exigences des WBAN. Pour valider l'utilité de ce protocole pour les WBAN, nous avons proposé d'évaluer, comme partie centrale de cette thèse, ses performances par une analyse formelle. Nous avons évalué les performances de ses méthodes d'accès Posting et CSMA/CA via le Model-Checker UPPAAL-SMC. Ensuite, nous avons amélioré les performances de la méthode d'accès CSMA/CA en termes de compteur d'attente (BC) et de fenêtre de contention (CW). Le Model-Checker UPPAAL-SMC peut fournir une interprétation stochastique du comportement stochastique des systèmes complexes et temps réel, tels que les WBAN. La modélisation et l'évaluation du comportement des protocoles MAC via les spécifications des automates temporisés stochastiques (STA) et de la logique temporelle d'intervalle métrique (MITL) adoptées par UPPAAL-SMC, nécessitent un certain niveau d'expertise. La chose qui n'est pas disponible pour de nombreux concepteurs de protocoles MAC. Pour faciliter l'utilisation des puissants algorithmes d'analyse d'UPPAAL-SMC, nous avons proposé de définir un prototype d'une approche d'ingénierie dirigée par les modèles (MDE) qui utilise un langage de modélisation spécifique au domaine (DSML) comme point de départ et UPPAAL-SMC comme cible.

Mots-clefs : Réseau de capteurs corporel sans fil, Contrôle d'accès au support, Norme IEEE 802.15.6, CSMA/CA, Vérification formelle, UPPAAL-SMC, Ingénierie dirigée par les modèles.

Abstract

This thesis focuses on the performance evaluation of medium access control (MAC) protocols for the wireless body area network (WBAN) through formal verification methods. The importance of WBANs encouraged the researchers to propose new MAC protocols to satisfy the WBAN requirements, the thing that led us to elaborate, as a first work, a quantitative and qualitative comparative analysis of the existing MAC protocols for WBANs. According to our comparison results, the MAC protocol of the IEEE Standard 802.15.6 considers most of the WBAN requirements. To validate its usefulness for the WBAN, we proposed to evaluate, as the thesis's central part, its performance through formal analysis. We evaluated the performance of its Posting and CSMA/CA access methods through the model-checker UPPAAL-SMC. Then, we enhanced the performance of the CSMA/CA access method in terms of the backoff counter (BC) and the contention window (CW). The model-checker UPPAAL-SMC can provide a stochastic interpretation of the stochastic behaviour of complex and real-time systems, such as WBANs. Modelling and evaluating the behaviour of MAC protocols through the stochastic timed automata (STA) and the metric interval temporal logic (MITL) specifications adopted by UPPAAL-SMC, necessitate a certain level of expertise. The thing that is not available for many MAC protocol designers. To facilitate the use of UPPAAL-SMC powerful analysis algorithms, we proposed to define a prototype of a model-driven engineering (MDE) approach that uses a domain-specific modelling language (DSML) as a start and the UPPAAL-SMC as a target.

Keywords: Wireless body area network, Medium access control, IEEE Standard 802.15.6, CSMA/CA, Formal verification, UPPAAL-SMC, Model-driven engineering.

Résumé Détaillé

Chapitre 1. 1.1 Motivations. La principale cause de décès dans le monde est la maladie cardiovasculaire, qui représente 30% de tous les décès dans le monde. Selon l'organisation mondiale de la santé, environ 17,5 millions de personnes dans le monde meurent chaque année de crises cardiaques ou d'accidents vasculaires cérébraux (AVC). Ces décès peuvent souvent être évités s'ils sont détectés à un stade précoce. Dans le monde, plus de 246 millions de personnes souffrent de diabète, un nombre qui devrait atteindre 380 millions d'ici 2025. Une surveillance fréquente permet un dosage approprié et réduit le risque d'évanouissement et, plus tard, de cécité, de perte de circulation et d'autres complications. Ces exemples illustrent déjà la nécessité d'un suivi médical continu. Les procédures de surveillance médicale nécessitent généralement la fixation de plus d'un capteur sur le corps humain. Par exemple, les patients à risque d'AVC doivent non seulement observer leurs simples valeurs de tension artérielle, mais surveiller à long terme des paramètres supplémentaires liés à la saturation en oxygène du sang, à la température et au poids. La technologie de surveillance actuelle nécessite le câblage des patients pour qu'ils portent un ensemble d'éléments capteurs filaires, reliés à plusieurs dispositifs de traitement et de visualisation des signaux des capteurs. Cela entraîne une augmentation des coûts des soins de santé par la nécessité d'une surveillance hospitalière des patients, ce qui affecte considérablement la qualité de vie. Par conséquent, en utilisant la technologie de surveillance des systèmes de soins de santé sans fil, un large éventail de maladies pourraient être prévenues, traitées et gérées plus efficacement, ce qui se traduirait par des améliorations majeures de la qualité de vie. Dans ce cas, même la surveillance des signaux vitaux tels que la fréquence cardiaque permet aux patients de vaquer à leurs activités normales au lieu de rester à la maison ou à proximité d'un service médical spécialisé. Cela ne peut être réalisé que par un réseau sans fil composé de capteurs et d'actionneurs intelligents, de faible puissance, de micro et nanotechnologie, qui peuvent être placés sur le corps, ou implantés dans le corps (ou même dans la circulation sanguine) offrant la qualité de service, la sécurité, la fiabilité, la priorité et l'évolutivité de la communication de données. Les réseaux sans fil existants ne répondent pas aux exigences en termes de minimisation du rayonnement, de consommation d'énergie de transmission et de limitation de la portée juste pour correspondre aux dimensions du corps humain, où un schéma de réseau sans fil adéquat doit être proposé. Le besoin d'une telle nouvelle technologie a suscité un intérêt croissant de la part des chercheurs, des concepteurs de systèmes et des développeurs d'applications pour un nouveau type d'architecture de réseau sans fil généralement connu sous le nom de réseau corporel sans fil (WBAN), rendu possible par de nouvelles avancées sur capteurs portables de surveillance légers, de petite taille, ultra-basse consommation et intelligents.

1.2 Problèmes. 1) Antenne : comme les capteurs et les antennes d'un réseau corporel sans fil seront conçus pour être aussi petits que possible, l'antenne sera proche du corps, ce qui entraînera une perte de trajet plus élevée : la complexité de la structure des tissus humains , la forme du corps et les mouvements du corps affectent la propagation des ondes électromagnétiques (EM). La propagation des ondes électromagnétiques dans le corps humain a été étudiée. Les résultats montrent que le corps agit comme un canal de communication où les pertes sont principalement dues à l'absorption d'énergie dans les tissus, qui est dissipée sous forme de chaleur. Comme le tissu est avec perte et se compose principalement d'eau, les ondes EM sont considérablement atténuées avant d'atteindre le récepteur. L'influence de la forme et de la position du corps d'un patient sur le diagramme de rayonnement d'un émetteur radio implanté a également été étudiée. Les résultats ont conclu que la différence entre les formes corporelles (c'est-à-dire homme, femme et enfant) est au moins aussi grande que l'impact des mouvements des bras d'un patient. Le mouvement du corps joue un rôle important dans la force du signal reçu. Les mouvements du bras vers l'avant et le côté du corps peuvent avoir un léger impact sur la puissance reçue. Des variations plus importantes sont constatées lorsque les bras sont déplacés de sorte qu'ils bloquent la ligne de visée entre les deux antennes. Plusieurs chercheurs ont étudié la perte de trajet le long et à l'intérieur du corps humain. Par exemple, des recherches préparatoires à l'institut Fraunhofer pour les circuits intégrés - électronique appliquée ont montré qu'une approche de transmission par radiofréquence est la plus adéquate pour les applications médicales. Les études ont été réalisées dans différentes bandes de fréquences, à savoir 402-405 MHz pour les capteurs implantés, 13,5 MHz, 5-50 MHz, 400 MHz, 600 MHz, 900 MHz, 2,4 GHz et 3,1-10,6 GHz pour les capteurs corporels. Ces bandes de fréquences doivent être prises en charge par la couche physique. 2) Capacité de la batterie : la taille de la batterie utilisée pour stocker l'énergie est dans la plupart des cas le plus grand contributeur au dispositif de capteur en termes de dimensions et de poids. Les batteries sont, par conséquent, maintenues petites et la consommation d'énergie des appareils doit être réduite. Cependant, l'exigence de faible consommation d'énergie entraîne une augmentation des retards de trame et une diminution du débit. 3) Taille des paquets : la petite taille des paquets générés par les capteurs conduit à une faible capacité de performance en termes de débit. 4) Hétérogénéité des nœuds : les nœuds de capteurs sont hétérogènes, ils ont des durées de vie de batterie, des limites de consommation d'énergie, des limites de mémoire, des débits de données et des priorités de données différentes qui affectent les communications entre les nœuds de capteurs. Pour surmonter ces problèmes, un protocole de contrôle d'accès au médium (MAC) adéquat avec des opérations efficaces, telles que des protocoles MAC économes en énergie et des protocoles offrants la qualité de service, doit être conçu. L'objectif principal des protocoles MAC est d'organiser le temps d'accès au médium partagé (canal) entre les nœuds. En raison du rôle important des protocoles MAC pour le WBAN, des efforts de recherche considérables sont consacrés à proposer de nouveaux protocoles MAC afin de satisfaire toutes les exigences strictes du WBAN, telles que l'efficacité énergétique et la qualité de service.

1.3 Contributions. L'objectif principal de ce travail de thèse est l'analyse des protocoles MAC du WBAN en se basant sur une méthode formelle. Ce dernier a la capacité d'augmenter la compréhension des systèmes en révélant les ambiguïtés, les lacunes et les incohérences qui ne peuvent être détectées par les tests de programmes. Le WBAN est considéré comme un environnement stochastique, où la prédiction du moment où les paramètres physiologiques changent de valeur est non déterministe. Le problème est de savoir comment modéliser et évaluer le comportement des protocoles MAC sous la nature stochastique du WBAN. L'ensemble d'outils de vérification de modèles statistiques UPPAAL-SMC a la capacité de fournir une interprétation stochastique du comportement stochastique des systèmes complexes et en temps réel, tels que les WBAN, et il est basé sur la méthode formelle de vérification de modèles statistiques (SMC). Nous subdivisons l'objectif principal de la thèse en sous-objectifs définis comme suit :

- Élaboration d'une analyse comparative quantitative et qualitative des protocoles MAC existants qui prennent en charge les exigences WBAN. La norme IEEE 802.15.6 est le résultat de l'analyse comparative. Il est défini par l'IEEE 802 (Institute of Electrical and Electronics Engineers). En novembre 2007, l'IEEE 802 a créé un groupe appelé IEEE 802.15.6 pour la normalisation du WBAN. Sa version finale est publiée en février 2012. Sa proposition est de définir deux nouvelles couches que sont la couche physique (PHY) et la couche MAC.

- Évaluation des performances des méthodes d'accès du protocole MAC de la norme IEEE 802.15.6. Nous considérons l'évaluation de métriques liées à l'efficacité énergétique, à la qualité de service, et à l'évolutivité:
  - Évaluation des performances de la méthode d'accès Posting. Nous utilisons UPPAAL-SMC pour évaluer l'évolutivité de la méthode d'accès Posting en fonction de l'énergie consommée par le hub et du débit.
  - Évaluation des performances de la méthode d'accès multiple avec écoute de porteuse et évitement de collision (CSMA/CA) via UPPAAL-SMC. Afin de procéder à l'évaluation, nous estimons l'efficacité énergétique, le débit et le délai en fonction de la moyenne maximale du nombre de collisions, la valeur du temps d'attente dans les sources d'écoute inactives et le nombre de paquets transmis avec succès.

- Amélioration des performances de la méthode d'accès CSMA/CA : puisque la méthode d'accès CSMA/CA souffre généralement de la perte de ses performances avec l'augmentation de la densité du réseau. Où la consommation d'énergie augmente pendant les transmissions et pendant les périodes d'attente et d'écoute. De plus, le mécanisme d'évitement des collisions devient inactif en raison de problèmes de chevauchement et de surécoute. Ces limitations sont la raison de l'amélioration de la méthode d'accès CSMA/CA.

- Pour faciliter l'utilisation des algorithmes d'analyse d'UPPAAL-SMC, nous proposons de définir le prototype d'une approche d'ingénierie dirigée par les modèles (MDE) qui utilise un langage de modélisation spécifique au domaine (DSML) comme point de départ et UPPAAL-SMC comme cible et retour. Le DSML proposé est dédié à la modélisation du comportement des protocoles MAC du WBAN.

Chapitre 2. L'objectif principal des protocoles MAC est d'organiser le temps d'accès au médium partagé entre les nœuds. Nous distinguons deux approches pour choisir le moment d'accès au médium : les protocoles basés sur la contention et les protocoles basés sur l'ordonnancement. Dans le cas des protocoles basés sur la contention, plusieurs nœuds seront en concurrence pour la même ressource en utilisant des méthodes basées sur la contention telles que l'accès multiple avec écoute de porteuse et évitement de collision (CSMA/CA). Alors que les protocoles basés sur l'ordonnancement visent à réserver une ressource pour chaque nœud en utilisant des méthodes basées sur l'ordonnancement telles que la méthode Posting. Dans ce chapitre, nous élaborons une analyse comparative quantitative et qualitative des protocoles MAC existants basés sur les exigences du WBAN. D'après les résultats de la comparaison, nous avons conclu qu'aucun protocole MAC ne prend en charge toutes les exigences strictes du WBAN. Bien que le rapport de la norme IEEE 802.15.6 indique que le protocole MAC de cette norme prend en charge plusieurs exigences. Par contre, il n'y a pas une évaluation complète qui affirme les performances de ce protocole, d'où vient notre contribution.

Chapitre 3. Posting est la méthode d'accès la plus importante pour le hub. Ce dernier s'en sert pour s'octroyer une allocation postée pour initier une ou plusieurs transactions de trame. Une allocation postée est un intervalle de temps d'allocation de liaison descendante, pendant lequel le hub peut desservir et transmettre un trafic de gestion et de données inattendu ou supplémentaire au nœud. Par exemple, il est utilisé dans le cas de besoins de gestion de réseau, de variations de débit de données et de dégradations de canaux. En raison du rôle important du hub dans le WBAN, en tant que dispositif de contrôle et de surveillance, il est important d'évaluer l'évolutivité de sa méthode d'accès Posting. L'évolutivité représente la capacité du réseau à continuer à fonctionner avec les mêmes performances malgré l'ajout d'autres nœuds. La validation de cette propriété permet de valider la méthode d'accès Posting et donc la performance du WBAN. Dans ce chapitre, nous proposons d'utiliser l'ensemble d'outils de vérification de modèle statistique UPPAAL-SMC pour étudier la méthode d'accès Posting dans l'environnement stochastique du WBAN. En se basant sur UPPAAL-SMC, nous modélisons et évaluons le comportement de la méthode d'accès Posting en termes d'évolutivité. Nous utilisons d'abord le formalisme des automates temporisés stochastiques (STA) fourni par UPPAAL-SMC pour construire un modèle détaillé de ce comportement. Ensuite, nous utilisons les spécifications de la logique temporelle d'intervalle métrique (MITL) adoptées par UPPAAL-SMC pour évaluer l'évolutivité de ce comportement. En plus d'évaluer l'évolutivité en fonction de l'énergie consommée par le hub et du débit, qui sont respectivement le problème dominant et la propriété de performance clé que nous devons valider pour le WBAN. Il faut aussi évaluer le nombre d'intervalles de temps d'allocation affichés du hub. Cette propriété montre la capacité du hub à toujours communiquer avec les nœuds malgré la croissance de la densité du réseau. À la suite de cette étude, avec la méthode d'accès Posting, le hub fonctionne avec les mêmes performances, même avec l'augmentation de la densité du réseau. Ainsi, valider l'évolutivité de la méthode d'accès Posting, et donc, valider l'évolutivité du WBAN.

Chapitre 4. Dans le cas de la fréquence à bande étroite (402 à 405 MHz), le protocole MAC de la norme IEEE 802.15.6 utilise le mécanisme d'accès multiple avec écoute de porteuse et évitement de collision (CSMA/CA) dans le mode de Superframes. Sa structure comporte quatre phases d'accès de type. Pour transmettre le trafic de données d'urgence, des phases d'accès exclusif (EAP1 et EAP2) sont utilisées. Pour le trafic de données normal, prioritaire ou d'urgence, les phases d'accès aléatoire (RAP1 et RAP2) et les phases d'accès conflictuel (CAP) conviennent. Pour le trafic de données périodique, la phase d'accès géré (MAP) est adéquate. Le mécanisme CSMA/CA est largement utilisé par de nombreux protocoles MAC. Par exemple, il fait partie du protocole MAC de la norme IEEE 802.11 , conçu pour les réseaux locaux sans fil (WLAN). Il est également utilisé dans le protocole MAC de la norme IEEE 802.15.4, dédié aux réseaux sans fil à faible débit et faible consommation. Parallèlement, il fait partie du protocole MAC de la norme IEEE 802.15.6, le centre de notre travail. Le CSMA/CA du protocole MAC de la norme IEEE 802.15.6 est une méthode d'accès basée sur la contention, par laquelle un nœud obtient des allocations dans les EAP, RAP ou CAP, pour initier une ou plusieurs transactions de trame pour le trafic de données imprévisible. En raison de la sensibilité des données médicales, l'évaluation et l'amélioration des performances de la méthode d'accès CSMA/CA sont cruciales. D'autant plus que le procédé d'accès CSMA/CA souffre généralement de la perte de ses performances avec l'augmentation de la densité du réseau : la consommation d'énergie augmente pendant les transmissions et pendant les périodes d'écoute et d'attente. De plus, le mécanisme d'évitement des collisions devient inactif en raison de la procédure de sélection du compteur d'attente (BC) ou de l'augmentation du nombre de nœuds cachés. Ces limitations sont la raison de nombreuses évaluations et modifications de CSMA/CA, comme dans le cas de notre contribution. Dans ce chapitre, nous évaluons les performances de la méthode d'accès CSMA/CA de la norme IEEE 802.15.6 en ce qui concerne les exigences du WBAN. Afin de procéder à l'évaluation, nous estimons l'efficacité énergétique, le débit et le délai de transmission en fonction de la moyenne maximale de: (1) le nombre de collisions, (2) la valeur du temps d'attente dans les sources d'écoute inactives et (3) le nombre de paquets transmis avec succès. Pour effectuer l'évaluation, nous utilisons l'ensemble d'outils de vérification de modèles statistiques UPPAAL-SMC. Pour la méthode d'accès CSMA/CA de la norme IEEE 802.15.6, les résultats de l'évaluation ont montré que dans la condition de saturation, les longueurs courtes et fixes des phases d'accès (RAP1, RAP2 et CAP) ne pouvaient pas couvrir le trafic moyen et élevé. Les intervalles convergés de la fenêtre de contention (CW) pour les priorités de l'utilisateur (UP5, UP6, UP7) augmentent le nombre de collisions. De plus, les sources d'écoute inactives conduisent à passer plus de temps d'attente dans ces endroits. Par conséquent, les performances du WBAN sont affectées négativement en termes d'efficacité énergétique, de débit et de délai de transmission.

Chapitre 5. Pour améliorer les performances de la méthode d'accès CSMA/CA de la norme IEEE 802.15.6, nous proposons une phase d'accès de durée variable en fonction de la charge de trafic. Ceci est le résultat de l'impact négatif qu'il a montré sur la structure du Superframe. Dans un second temps, nous proposons une optimisation des sources d'écoute inactives de la méthode d'accès CSMA/CA. Troisièmement, pour le problème du mécanisme d'évitement des collisions, qui est représenté par les intervalles convergés de CW, nous avons l'intention d'appliquer une nouvelle distribution des intervalles de CW pour diminuer la probabilité de collisions, ainsi qu'une procédure de sélection BC sous ces CW proposés. Pour notre procédure de sélection BC proposée, les résultats de l'évaluation ont montré qu'elle a un impact positif sur la moyenne du nombre maximal de collisions et du nombre maximal de paquets transmis avec succès. Cette proposition a réussi à réduire de plus de moitié le nombre de collisions obtenues lors de la première évaluation de la méthode d'accès CSMA/CA. Par conséquent, cette baisse a entraîné une légère augmentation de la moyenne du nombre maximal de paquets transmis avec succès par rapport aux résultats obtenus lors de la première évaluation de la méthode d'accès CSMA/CA. Cependant, à partir des deux évaluations, nous sommes arrivés à confirmer que la division du Superframe en phases d'accès courtes et fixes et la construction de la méthode d'accès CSMA/CA avec un nombre élevé de sources d'écoute inactives sont toujours les problèmes qui dégradent les performances de la méthode d'accès CSMA/CA , par conséquent, les performances du WBAN. Dans des travaux futurs, nous avons l'intention de proposer une nouvelle architecture qui exploite l'inefficacité de la structure du Superframe et l'optimisation des sources d'écoute inactives de la méthode d'accès CSMA/CA de la norme IEEE 802.15.6.

Chapitre 6. La modélisation et l'évaluation du comportement des protocoles MAC du WBAN via l'ensemble d'outils de vérification de modèles statistiques UPPAAL-SMC nécessitent un certain niveau d'expertise de ce côté. La chose qui n'est pas disponible pour nombreux concepteurs de protocoles MAC. Pour faciliter l'utilisation d'UPPAAL-SMC, nous proposons de définir une approche d'ingénierie dirigée par les modèles (MDE) qui utilise une méthode de modélisation (MM) comme point de départ et UPPAAL-SMC comme cible et inversement. Dans ce chapitre, nous utilisons la plate-forme ADOxx pour définir, comme première partie de cette MM de WBAN (WBAN-MM), le langage de modélisation spécifique au domaine (DSML) du WBAN qui est présenté sous le nom de langage de modélisation de WBAN (WBAN-ML) pour modéliser le comportement des protocoles MAC du WBAN.

Chapitre 7. Dans ce chapitre, nous en venons à conclure ce qu'on a fait dans les chapitres précédents. Dans le chapitre 1, on a donné une introduction du travail de cette thèse par la définition des motivations, des problèmes, et des contributions. Dans le chapitre 2, nous avons énoncé la définition, les composants, l'architecture de communication, les exigences et les protocoles MAC existants du WBAN. De plus, nous avons comparé les protocoles MAC existants du WBAN et nous avons répertorié les études qui ont évalué et amélioré les performances de la méthode d'accès CSMA/CA de la norme IEEE 802.15.6. À la suite de cet examen détaillé, jusqu'à présent, aucun protocole MAC ne prend en charge toutes les exigences strictes du WBAN, et il n'y a pas d'évaluation complète des performances ou d'amélioration de la méthode d'accès CSMA/CA. Dans le chapitre 3, nous avons utilisé l'ensemble d'outils de vérification de modèles statistiques UPPAAL-SMC pour étudier la méthode d'accès Posting dans l'environnement stochastique du WBAN. En se basant d'UPPAAL-SMC, nous avons modélisé et évalué le comportement de la méthode d'accès Posting en termes de l'évolutivité. D'après les résultats de l'évaluation des performances, nous avons conclu que le hub fonctionne avec les mêmes performances, même avec l'augmentation de la densité du réseau. Ainsi, valider l'évolutivité de la méthode d'accès Posting, et donc, valider l'évolutivité du WBAN. Dans le chapitre 4, nous avons évalué, à l'aide de l'ensemble d'outils de vérification de modèles statistiques UPPAAL-SMC, les performances de la méthode d'accès CSMA/CA de la norme IEEE 802.15.6, en ce qui concerne les exigences du WBAN. Grâce à une étude de cas, nous avons analysé quantitativement l'efficacité énergétique, le débit et le délai de transmission en fonction de la moyenne du maximum nombre de collisions, de temps d'attente dans les sources d'écoute inactives et du nombre de paquets transmis avec succès. Les résultats de l'évaluation des performances ont montré que dans la condition de saturation, les longueurs courtes et fixes des phases d'accès (RAP1, RAP2 et CAP) ne pouvaient pas couvrir le trafic moyen et élevé. Les intervalles convergés de la fenêtre de contention (CW) pour les priorités de l'utilisateur (UP5, UP6, UP7) augmentent le nombre de collisions. De plus, les sources d'écoute inactives conduisent à passer plus de temps d'attente dans ces endroits. Par conséquent, les performances du WBAN sont affectées négativement en termes d'efficacité énergétique, de débit et de délai de transmission. Pour le chapitre 5, les résultats d'évaluation de notre procédure de sélection du compteur d'attente (BC) proposée ont confirmé son impact positif sur la moyenne du nombre maximal de collisions et du nombre maximal de paquets transmis avec succès. Cette proposition a réussi à réduire de plus de moitié le nombre de collisions obtenues lors de la première évaluation de la méthode d'accès CSMA/CA de la norme IEEE 802.15.6. Par conséquent, cette baisse a entraîné une légère augmentation de la moyenne du nombre maximal de paquets transmis avec succès par rapport aux résultats obtenus lors de la première évaluation de la méthode d'accès CSMA/CA. Cependant, à partir des deux évaluations, nous sommes arrivés à confirmer que la division du Superframe en phases d'accès courtes et fixes et la construction de la méthode d'accès CSMA/CA avec un nombre élevé de sources d'écoute inactives sont toujours les problèmes qui dégradent les performances de la méthode d'accès CSMA/CA, par conséquent, les performances du WBAN. Cette proposition a une extension qui est présentée en annexe. La proposition de cette extension est de minimiser le nombre de périodes d'attente et d'écoute inactives. Ainsi que, pour surmonter les problèmes de collision, tels que le chevauchement et la surécoute grâce à l'introduction du temps unique d'écoute du canal pour chaque nœud et la proposition d'une longueur de Slot adaptative et flexible. Concernant la proposition de la méthode de modélisation de WBAN dans le chapitre 6, nous concluons que nous avons implémenté le prototype du langage de modélisation de WBAN qui doit être modifié et validé.

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Chapter 1

General Introduction

1.1 Thesis context

1.1.1 Motivations

The main cause of death in the world is cardiovascular disease, representing 30% of all global deaths. According to the world health organization, world-wide about 17.5 million people die of heart attacks or strokes each year. These deaths can often be prevented if they are detected in their early stages. Worldwide, more than 246 million people suffer from diabetes, a number that is expected to rise to 380 million by 2025. Frequent monitoring enables proper dosing and reduces the risk of fainting and in later life blindness, loss of circulation and other complications. These examples already illustrate the need for continuous medical monitoring. Medical monitoring procedures usually require more than one sensor to be attached to the human body. For instance, stroke risk patients not only should observe their mere blood pressure values, but supervise additional parameters related to blood oxygen saturation, temperature and weight on a long-term basis. Current monitoring technology requires cabling of patients to wear a set of wired sensor elements, linked to several devices for processing and visualization of the sensor signals. That is leading to increase health care costs by the need for in-hospital monitoring of patients, significantly, affecting the quality of life. Therefore, using wireless health care systems monitoring technology, a wide range of diseases could be prevented, treated and managed more effectively, and resulting in major improvements in the quality of life. In this case, even monitoring vital signals such as the heart rate allows patients to engage in their normal activities instead of staying at home or close to a specialized medical service. This can only be achieved through a wireless network consisting of intelligent, low-power, micro and nano-technology sensors and actuators, which can be placed on the body, or implanted in the body (or even in the blood stream) providing the quality of service, the security, the reliability, the priority, and the scalability of data communication. Existing wireless networks do not meet the requirements in terms of minimizing radiation, transmission power consumption, and limiting range to just match the range of human body dimensions, where an adequate wireless network schema have to be proposed: while this latter is devoted to the interconnection of one person's wearable devices with transmission short range that cover typically 2 m, a wireless personal area network (WPAN) is a network in the environment around the person with transmission range that can reach 10 m, a wireless local area network (WLAN) has a typical transmission range up to hundreds of meters. The need of such new technology (body wearable devices monitoring) has been increasing interest from researchers, system designers, and application developers on a new type of wireless network architecture generally known as wireless body area network (WBAN), made feasible by novel advances on lightweight, small-size, ultra-low-power, and intelligent monitoring wearable sensors (Schmidt et al., 2002; Latré et al., 2011; Movassaghi et al., (2014)).

1.1.2 Challenges

Antenna (Schmidt et al., 2002; Latré et al., 2011; Movassaghi et al., (2014)): as the sensors and antennas of a wireless body area network will be designed to be as small as possible, the antenna will be close to the body, which will result in a higher path loss: the complexity of human tissues' structure, the body shape and the body movements affect the propagation of electromagnetic (EM) waves. The propagation of electromagnetic waves in the human body has been investigated. The results show that the body acts as a communication channel where losses are mainly due to the absorption of power in the tissue, which is dissipated as heat. As the tissue is lossy and mostly consists of water, the EM waves are attenuated considerably before they reach the receiver. The influence of a patient's body shape and position on the radiation pattern from an implanted radio transmitter has been studied also. The results concluded that the difference between body shapes (i.e. male, female and child) is at least as large as the impact of a patient's arm movements. The movement of the body plays an important role in the strength of the received signal. The arm motions to the front and side of the body can have a small impact on the received power. More significant variations are found when the arms are moved so that they block the line of sight between the two antennas. Several researchers have been investigating path loss along and inside the human body. For example, preparatory research at the Fraunhofer Institute for Integrated Circuits - Applied Electronics has shown that a radio frequency transmission approach is most adequate for medical applications. The studies have been done in various frequency bands, i.e., 402-405 MHz for implanted sensors, 13.5 MHz, 5-50 MHz, 400 MHz, 600 MHz, 900 MHz, 2.4 GHz and 3.1-10.6 GHz for on-body sensors. These frequency bands should be supported by the physical layer.

Battery capacity (Schmidt et al., 2002; Latré et al., 2011; Movassaghi et al., (2014)): the size of the battery used to store the energy is in most cases the largest contributor to the sensor device in terms of both dimensions and weight. Batteries are, as a consequence, kept small and energy consumption of the devices needs to be reduced. However, the low power consumption requirement leads to increase frame delays and decrease throughput. Packet size (Schmidt et al., 2002; Latré et al., 2011; Movassaghi et al., (2014)): the small packet size generated by the sensors, leads to a low-performance capacity in terms of throughput. Node heterogeneity (Schmidt et al., 2002; Latré et al., 2011; Movassaghi et al., (2014)): sensor nodes are heterogeneous, they have different battery lifetimes, power consumption limits, memory limits, data rates, and data priorities that affect the communications between sensor nodes. To overcome these challenges, an adequate medium access control

(MAC) protocol with efficient operations, such as energy-efficient MAC protocols and QoS-MAC protocols should be designed. The primary goal of MAC protocols is to organize the access time to the shared medium (channel) between nodes. We distinguish two approaches for choosing the moment of access to the medium: contention-based protocols and program-based or schedule-based protocols. In the case of contention-based protocols, several nodes will compete for the same access time by using contention-based methods. In contrast, the schedule-based protocols aim to reserve an access time for each node using schedule-based methods.

1.2 Thesis objectives

Due to the important role of MAC protocols for WBAN, considerable research efforts are dedicated to propose new MAC protocols in order to satisfy all the stringent requirements of WBAN, such as the energy-efficiency and the quality of service. The principal objective of this thesis work is the analysis of the MAC protocols for WBANs based on a formal method. This latter has the ability to increase the understanding of the systems by revealing ambiguities, incompletenesses, and inconsistencies that can not be detected by program testing. The WBAN is considered as a stochastic environment, where the prediction of the time when the physiological parameters change their values is non-deterministic. The problem is how to model and evaluate the behavior of the MAC protocols under the stochastic nature of the WBAN. The statistical model-checking toolset UPPAAL-SMC has the ability to provide a stochastic interpretation of the stochastic behavior of complex and real-time systems, such as WBANs, and it is based on the statistical model-checking (SMC) formal method. We subdivide the principal thesis objective into sub-objectives as defined as follows:

1. Elaborating a quantitative and qualitative comparative analysis of the existing MAC protocols that support the WBAN requirements. The IEEE Standard 802.15.6 is the result of the comparative analysis. It is defined by the IEEE 802 (Institute of Electrical and Electronics Engineers). In November 2007, the IEEE 802 created a group called IEEE 802.15.6 for the standardization of WBAN. Its final version is published in February 2012 (Association et al., 2012). Its proposal is to define two new layers that are the physical layer (PHY) and the MAC layer. Short-range, wireless communications in the vicinity of, or inside, a human body are specified in this standard. It uses existing industrial scientific medical (ISM) bands as well as frequency bands approved by national medical and/or regulatory authorities. Support for quality of service, extremely low power and data rates up to 10 Mbps is required. This standard considers effects on portable antennas due to the presence of a person (varying with male, female, skinny, heavy, etc.), radiation pattern shaping to minimize the specific absorption rate (SAR) into the body, and changes in characteristics as a result of the user motions. The IEEE Standard 802.15.6 organizes the nodes into one- or two-hop star topology. A single control and monitoring device controls the entire operation of each WBAN. The WBAN must have one control and monitoring device (i.e., the hub) and a number of

sensors nodes, ranging from 0 to 64. The standard divides the time axis into superframes of equal length, for beacon, and non-beacon access modes with superframes. Time is split into intervals for non-beacon access mode without superframes. Moreover, the standard classifies the data frames into eight user priorities (UP0, UP1, UP2, UP3, UP4, UP5, UP6, and UP7).

2. Performance evaluation of the MAC access methods of the IEEE Standard 802.15.6. We consider the evaluation of specific WBAN applicative metrics related to the energy-efficiency, the quality of service (throughput and delay), and the scalability requirements:
    (a) Performance evaluation of the posting scheduled-based access method: we use the UPPAAL-SMC to evaluate the scalability of the posting access method according to the energy consumed by the hub and the throughput, which are the dominant problem and the key performance, respectively, properties that we should validate for WBAN.
    (b) Performance evaluation of the CSMA/CA contention-based access method through UPPAAL-SMC: in order to proceed with the evaluation, we estimate the energy-efficiency, throughput, and delay according to the maximal average of the number of collisions, the value of waiting time in idle listening sources, and the number of packets successfully transmitted. The energy consumption is the dominant problem of MAC protocols design in wireless sensor networks. Its sources are communication, followed by processing, and sensing, in decreasing consumption order. The energy consumption during the communication task is due to transmission and reception power choice, collisions, and idle listening. The first two sources are the major sources of energy consumption. Collisions become the major source of energy consumption when their number increases in the network and, the idle listening becomes the major source of energy consumption when the nodes spend a long idle time listening to the channel. To know how the CSMA/CA access method exploits the energy-efficiency during the communication task, we propose to evaluate its behavior in terms of collisions and waiting time in idle listening locations.

3. Performance enhancement of the CSMA/CA access method: since the CSMA/CA access method generally suffers from the loss of its performance with the increase of the network density. Where the energy consumption increases during the transmissions and during the idle listening and waiting time periods. As well, the collision avoidance mechanism becomes inactive due to overlapping and overhearing problems. These limitations are the reason for the enhancement of the CSMA/CA access method. The overhearing problem means the inability of a node to detect the data transmission of another node (hidden nodes) in the shared medium, which leads to collisions. To prevent this problem, a back-off counter is proposed. The overlapping problem means that the nodes transmit data at the same time when the nodes select the same back-off or when the nodes' backoffs reach zero a the same time, which results in collisions.

4. To facilitate the use of the formal method analysis algorithms, we propose to define the prototype of a model-driven engineering (MDE) approach that uses a domain-specific modeling language (DSML) as a start and the formal method toolset UPPAAL-SMC as a target. The proposed DSML is dedicated to the modeling behavior of the MAC protocols of the WBAN.

1.3 Thesis plan

The plan of this thesis dissertation is organized as follows: Chapter 2 represents the state of the art and backgrounds. Chapter 3 represents the formal analysis of the posting access method. Chapter 4 represents the formal analysis of the CSMA/CA access method. Chapter 5 represents the enhancement of the CSMA/CA access method. Chapter 6 represents the prototype of the WBAN modeling language. Chapter 7 concludes the thesis work.

1.4 Thesis publications

1. Bethaina Touijer, Yann Ben Maissa, Salma Mouline, “IEEE 802.15.6 CSMA/CA access method for WBANs: Performance evaluation and new backoff counter selection procedure”, Computer Networks, Elsevier, 2021, 188, 107759. Touijer, Maissa, and Mouline, 2021.

2. Bethaina Touijer, Yann Ben Maissa, Salma Mouline, “Scalability validation of the posting access method through UPPAAL-SMC model-checker”, International Journal of Advanced Computer Science and Applications, 2020, 11(8), pp. 722–730. Touijer, Maissa, and Mouline, 2020.

3. Bethaina Touijer, Yann Ben Maissa, Salma Mouline, “MAC protocols for Wireless Body Area Networks: An overview”, the 13th International Wireless Communications and Mobile Computing Conference, Valencia, Spain, 2017. Touijer, Maissa, and Mouline, 2017.

Chapter 2

Backgrounds and State of the Art

2.1 Wireless body area network

In this section, we present the principal concepts of the wireless body area network synthesized from many surveyed studies. We give its definition, components, communication architecture, and its stringent requirements.

2.1.1 Definition

The wireless body area network (WBAN) (Movassaghi et al., (2014)) is composed of bio-medical sensors nodes that can be worn on or placed in the human body to measure certain physiological parameters of the human body (e.g., temperature, pressure). These sensors nodes must wirelessly send their data to a control and monitoring device (e.g., coordinator) carried on the body. This device then delivers its data via a cellular or Internet network to an emergency center or a doctor room on the basis of which an action can be taken according to a specific medical application. WBAN medical applications (Schmidt et al., 2002) can be subdivided into professional and consumer ones. Professional applications are initiated and controled by a healthcare professional or physician. While consumer applications are within private responsability of user (e.g., body fitness).

2.1.2 Components

WBAN components are divided into three classes (Latré et al., 2011; Movassaghi et al., (2014)), which are the personal device, the actuator, and the sensors node:

Personal device: is called also coordinator, aggregator or hub. It collects all the informations acquired by the sensors nodes and actuators, then sends them to the user (e.g., the patient, a nurse, a doctor) via an external gateway.

Actuator: is a device that is acting according to the data received from the sensors nodes or by interaction with the user, i.e., such as an actuator with a reservoir and an integrated pump provides the correct dose of insulin to give it to diabetics based on glucose level measurements.

Sensors node: allows to measure certain internal and external parameters of the human body and to send these data to the personal device. It can integrate one or more actuators. The sensors are divided into three categories: physiological sensors, biokinetic sensors and ambient sensors:

- Physiological sensors: measure ambulatory blood pressure, continuous glucose monitoring, body temperature, oxygen in the blood, and signals related to inductive respiratory plethysmography, ElectroCardioGraph (ECG), ElectroEncephaloGraph (EEG) and ElectroMyoGraph (EMG).
- Biokinetic sensors: measure the acceleration of the sensors and the angular velocity of rotation resulting from human movement.
- Ambient sensors: measure environmental phenomena, such as humidity, light, sound, pressure level and temperature.

2.1.3 Communication

The communication architecture in the WBAN is divided into three tiers (or levels), which are the tier-1. Intra-WBAN, the tier-2. Inter-WBAN and the tier-3. Beyond-WBAN communications (Chen et al., 2011; Latré et al., 2011; Movassaghi et al., (2014)) :

tier-1: is the communication between the sensors nodes, actuators, and the coordinator in a space of 2 meters surrounding the human body. This tier is the functional part in the WBAN communication.

tier-2: is the communication between the coordinator and one or more access points. This communication interconnects the WBAN with several networks to facilitate the arrival of the data to the user.

tier-3: is the connection between tier-2 and the medical server via the Internet. In a medical application a database is one of the most important components of tier-3 as it includes medical history and user profile. Thus, doctors or patients can be informed of an emergency status either by Internet or by a short message service (SMS).

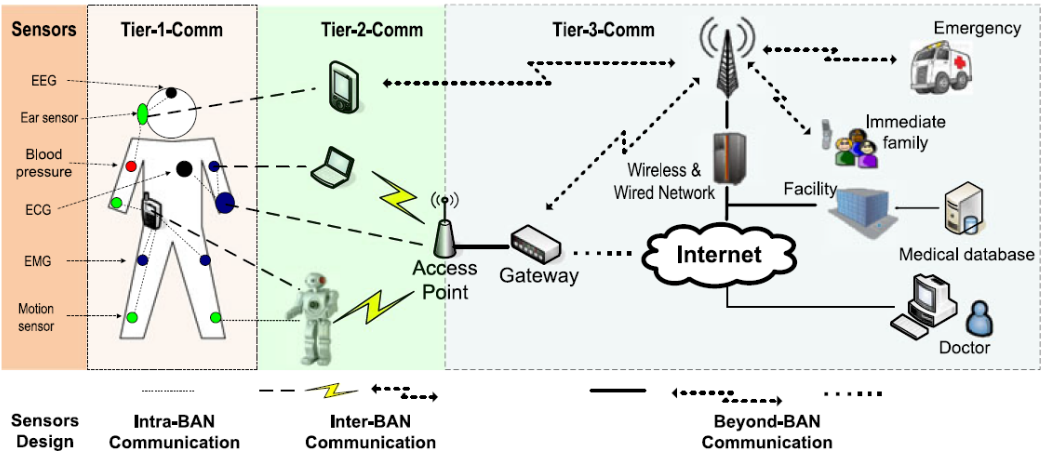


FIGURE 2.1: WBAN communication architecture tiers (Chen et al., 2011).

2.1.4 Requirements

WBAN presents several requirements, while energy-efficiency, quality of service, reliability, priority, scalability, security, and usability are the stringent requirements:

Energy-Efficiency (Isikman et al., 2011): the lifetime of the network must be long especially for the sensors nodes that are placed in the human body, which require a low energy consumption.

Quality of Service (QoS) (Movassaghi et al., (2014); Latré et al., 2011): Qos is important for the management and performance of WBAN medical applications. The crucial issue of QoS is the reliability of the transmission. It includes also the real-time transmission, end-to-end latency, and throughput.

Reliability (Movassaghi et al., (2014); Latré et al., 2011): it is necessary to guarantee the correct reception of the data in a limited time. It includes packet delivery ratio (PDR), bit error rate (BER), and transmission delay. The PDR measures the number of packets that reach the destination. The BER measures the ratio between the number of bits incorrectly received and the total number of bits transmitted. In WBAN medical application, the BER should be ranging between 10^{-10} et 10^{-4} and the transmission delay less than 250 ms.

Priority (Isikman et al., 2011): the WBAN must support different types of traffic, i.e., normal, periodic or emergency. The latter must have the priority.

Scalability (Movassaghi et al., (2014); Chen et al., 2011): the ability of the network to continue to operate with the same performance despite the addition of other nodes.

Security (Isikman et al., 2011; Latré et al., 2011): communication of health information between WBAN sensors nodes and servers via the Internet is strictly private and confidential and should be encrypted to protect the privacy life of patients.

Usability (Isikman et al., 2011; Latré et al., 2011): ease of use, self-configuration, and self-maintenance of sensors nodes especially for people who do not know how to use the new technologies.

The existing medium access control protocols supporting these requirements will be presented in the next section. The node(s) will refer, in the rest of this work, to the sensor(s) node(s).

2.2 Medium access control protocols

The primary goal of medium access control (MAC) protocols is to organize the access time to the shared medium between nodes. We distinguish two approaches for choosing the moment of access to the medium: contention-based protocols and program-based or schedule-based protocols. In the case of contention-based protocols, several nodes will compete for the same access time by using contention-based methods. In contrast, the schedule-based protocols aim to reserve an access time for each node using schedule-based methods. In this section, we present, in chronological order, the existing MAC protocols that are designed to support the WBAN requirements. First, we detail the protocols that support more than one requirement.

Then, we cite the other protocols that support mainly one requirement and, thereafter, we discuss all these protocols.

2.2.1 State of the art

IEEE 802.15.4 MAC protocol

IEEE 802.15.4 is a standard that was designed for low-rate personal area networks (PANs) (Li, Li, and Kohno, 2009; Xia and Rahim, 2015). The IEEE 802.15.4 MAC protocol supports two communication modes, and should operate in only one: beacon-enabled mode with superframe and non beacon-enabled mode without superframe. The beacon-enabled mode with superframe uses a Slotted Aloha or Slotted carrier sense multiple access with collision avoidance (CSMA/CA) methods in contention access period (CAP), and uses guaranteed time slots (GTSs) in contention free period (CFP). However, Unslotted CSMA/CA method is used by non beacon-enabled mode without superframe (Li, Li, and Kohno, 2009). In beacon-enabled mode, the coordinator transmits superframes periodically (Huang et al., 2015). The superframe is divided into an Active and an Inactive periods as depicted in Figure 2.2. The Active period of the superframe contains 16 equally spaced slots and composed of three parts: a Beacon, a CAP, and a CFP. The coordinator interacts with nodes during the Active period and sleeps during the Inactive period. The coordinator transmits beacon frames periodically in the beacon period to achieve synchronization of attached nodes, PAN identification, and to describe superframe's structure. During the CAP, a CSMA/CA method is used for data transmission. The CFP is optional and contains up to 7 GTSs in each superframe. GTSs are reserved for specified nodes to transmit time-critical packets. The simulation result in terms of energy consumption that are presented in (Liu, Yan, and Chen, 2013) shows that the power consumed by nodes and the coordinator depends on the duty cycle (DC), i.e., low DC means low power consumption. And, shows that the Slotted CSMA/CA method outperforms the other contention-based methods, because there is no Inactive period in Aloha and Unslotted CSMA/CA, which increases the power consumption.

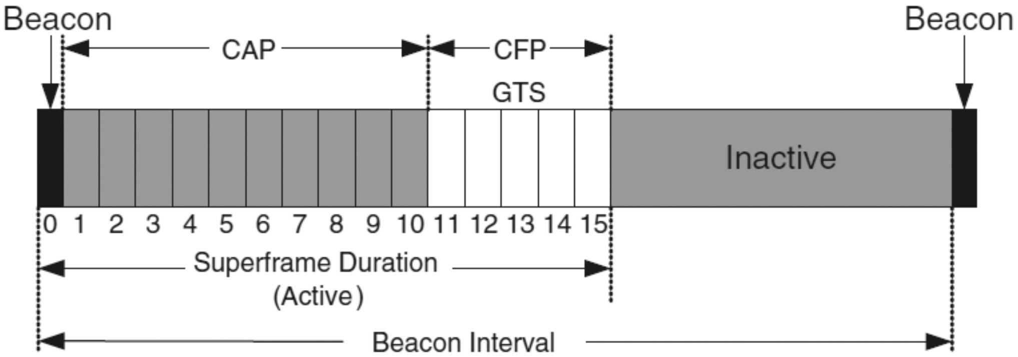


FIGURE 2.2: IEEE 802.15.4 MAC superframe structure (Huang et al., 2015).

SRMAC protocol

Li et al., 2009 proposed the scalable and robust MAC (SRMAC) protocol to support the WBAN scalability, meanwhile guarantee the QoS requirements, such as the decrease of packet latency and the increase of the success probability of transmission. SRMAC is based on the standard IEEE 802.15.4 MAC superframe structure. And, it changed the CSMA/CA method used in the CAP by the Slotted Aloha method with the concept of the mini-slot to increase the efficiency of the contention, i.e., the one slot in the superframe consists of four mini-slots associated to three command frames and one acknowledgement (ACK) frame. To make the CFP able to support more nodes in the network, the authors proposed the flexible and adaptive CFP duration to the traffic load. This duration may be zero if there is no CFP traffic. Or, it may occupy the whole active portion of the superframe. To evaluate the performance of SRMAC, specialy the performance of the mini-slot Aloha scheme, the authors implemented the proposed protocol. They considered a single WBAN of one coordinator and several nodes up to 30 nodes. The other simulation parameters are detailed in (Li et al., 2009). The results of the simulation show that the mini-slot Aloha outperforms the original Slotted Aloha in many metrics such as the energy-efficiency, the average packet delay, and the packet dropping rate. The efficiency of these parameters affects positively the success probability of transmission and scalability of WBAN.

LDTA-MAC protocol

Li et al., 2011 proposed low delay and traffic adaptivity-MAC (LDTA-MAC) protocol, which aims to decrease the energy consumption of the network devices and to reduce the average packet delay. LDTA-MAC is based on the IEEE 802.15.4 MAC superframe structure. And, it proposed a revised structure, whereby the durations of the CFP and of the Inactive period vary according to the dynamic allocation for GTS. Thus, it proposed a method to realize the dynamic GTS allocation. In LDTA-MAC, the structure of the superframe is divided into Beacon frame, Active and Inactive periods. The Beacon frame is used for timing and synchronization between the coordinator and all other nodes. The Active period is divided into a fixed CAP period and a dynamic CFP period. The CAP period is used by nodes to send to the coordinator the GTS requests. The CFP period is used by nodes to send to the coordinator their data. The coordinator responds the GTS requests under different response time, which is determined by the hardware implementation of the coordinator. The method used by coordinator to schedule GTS allocation time slots, serves at first the pre-existing GTSs allocation, then broadcasts a notification frame for informing all nodes about an extended CFP period that will be used to serve the current allocation requests. However, if all time slots are allocated the coordinator must broadcast in the notification frame of the next superframe. To evaluate the performance of this protocol in terms of energy consumption and average packet delay, the authors have implemented IEEE 802.15.4 MAC and LDTA-MAC on the platform of MIRAI-SF (Li et al., 2011). They considered two different scenarios of the coordinator response time to the GTS request. One scenario with response time of 100 *ms* and the other with 1000 *ms*. The other parameters used in the simulation are detailled in (Li et al., 2011). The simulation results show that LDTA-MAC is effective in reducing the packet delay, especially with a short time response for the GTS request. However, the energy consumed by nodes increases as a function of the increase of nodes number. Thus, LDTA-MAC consumes energy more than IEEE 802.15.4, because all nodes still active during the Active period.

McMAC protocol

Monowar et al., 2012 proposed multi-constrained QoS MAC (McMAC) protocol, which uses a novel superframe structure, that provides the access to the medium based on the traffic type. The simulation results that is implemented in ns-2 demonstrate the performance of the McMAC in terms of average packet delay, energy consumption and reliability, espacially the reliability of the emergency traffic.

IEEE 802.15.6 MAC protocol

The IEEE Standard 802.15.6 is defined by the IEEE 802 (Institute of Electrical and Electronics Engineers). In November 2007, the IEEE 802 created a group called IEEE 802.15.6 for the standardization of WBAN. Its final version is published in February 2012 (Association et al., 2012). His proposal is to define two new layers that are the physical layer (PHY) and the MAC layer. Short-range, wireless communications in the vicinity of, or inside, a human body (but not limited to humans) are specified in this standard. It uses existing industrial scientific medical (ISM) bands as well as frequency bands approved by national medical and/or regulatory authorities. Support for quality of service (QoS), extremely low power, and data rates up to 10 Mbps is required while simultaneously complying with strict non-interference guidelines where needed. This standard considers effects on portable antennas due to the presence of a person (varying with male, female, skinny, heavy, etc.), radiation pattern shaping to minimize the specific absorption rate (SAR) into the body, and changes in characteristics as a result of the user motions. The IEEE Standard 802.15.6 organizes the nodes into one- or two-hop star topology. A single control and monitoring device controls the entire operation of each WBAN. The WBAN must have one control and monitoring device (i.e., the hub) and a number of sensors nodes, ranging from 0 to 64. The standard divides the time axis into superframes of equal length, for beacon, and non-beacon access modes with superframes. Time is split into intervals for non-beacon access mode without superframes. Moreover, the standard classifies the data frames into eight user priorities (UP0, UP1, UP2, UP3, UP4, UP5, UP6, and UP7). In the next Section 2.3, we will define the concepts and present the studies of the IEEE 802.15.6 MAC protocol.

Other MAC protocols

There are other MAC protocols that have been designed for WBAN. The majority of them are proposed to support the energy-efficiency (Omeni et al., 2008; Li and Tan, 2009; Marinkovic et al., 2009; Marinkovic et al., 2009; Fang and Dutkiewicz, 2009; Alam et al., 2012a; Rahim et al., 2012; Al Ameen et al., 2012; Alam et al., 2012b; Ullah and Kwak, 2012; Yuan, Li, and Zhu, 2013; Mohammadi, Zhang, and Dutkiewicz, 2014; Jinbao and Lei, 2014; Ahmad et al., 2014; Upadhayay and Gupta, 2015; Ibarra et al., 2015; Yu and Kim, 2016; Rasheed et al., 2017). The primary source of the extra energy wastage is the periodical synchronization of the nodes with the coordinator, espacially for nodes with low duty cycle. In (Li and Tan, 2009; Alam et al., 2012a; Rahim et al., 2012) the authors exploited this problem. For instance in (Li and Tan, 2009), the protocol proposed aims to improve WBAN energy-efficiency by exploiting heartbeat rhythm information to perform time synchronization. The protocols (Kim and Cho, 2012; Ullah, Imran, and Alnuem, 2014; Kim, Kim, and Kim, 2015; Yu et al., 2016) are proposed to support the priority. A short discussion about these protocols will be presented in the next subsection.

2.2.2 Discussion

According to the MAC protocols presented in this section, we observe that many MAC protocols designed for WBAN focus principally on the energy-efficiency requirement. The energy consumption is the dominant problem of WBAN, specially for not chargeable nodes that are planted in the human body. As stated in the results of the simulations, the existing energy-efficient MAC protocols have not all treated effectively this problem, such as the LDTA-MAC protocol. The QoS requirement is also mostly supported in MAC protocols design, especially the data packet loss and the average packet delay metrics that are exploited very well in SRMAC, LDTA-MAC, and McMAC protocols. The efficiency of these metrics ensures the WBAN reliability. We note the same thing for the priority requirement that is supported and exploited very well by many protocols in terms of giving to the emergency data the transmission priority. The reliability requirement is treated with efficacy in McMAC and in (Omeni et al., 2008). This latter has proposed a special method to ensure the high transmission reliability, that is affirmed through simulation results. From this results, we can conclude that up to now, there is no MAC protocol that supports all the stringent requirements of WBAN. Although the report (Association et al., 2012) says that the IEEE 802.15.6 MAC protocol supports several requirements, but there is not a whole evaluation that affirms the performance of this protocol.

In the next chapters, we will evaluate the performance of the IEEE 802.15.6 MAC protocol to judge its usefulness for WBAN. While in the next section, we will define it and present the performance evaluation and enhancement studies of its CSMA/CA contention-based access method. Concerning scheduled-based access methods, there are just polling access method studies, the not considered method in this thesis work.

2.3 IEEE 802.15.6 MAC protocol

The IEEE 802.15.6 working group defines a MAC protocol to control channel access. As defined in (Association et al., 2012), the IEEE 802.15.6 MAC protocol supports three access modes: the beacon mode with superframes, the non-beacon mode with superframes, and the non-beacon mode without superframes, as depicted in Figure 2.3(a), Figure 2.3(b), and Figure 2.3(c), respectively. The time axis of the latter mode is divided into intervals, where the node and the hub can employ one or more access methods. However, the time axis of the other two access modes is divided into superframes of equal length, and each superframe is composed of allocation slots of similar length, numbered $0, 1, ..., s$, where $s <= 255$. The superframe can be divided into one or more access phases, where the node and the hub can employ one or more access methods. The access methods of the IEEE 802.15.6 MAC protocol are divided into five classes: scheduled, scheduled-polling, unscheduled, improvised, and contention, as depicted in Figure 2.3(a), Figure 2.3(b), and Figure 2.3(c).

The scheduled access method is based on advance reservation and committed schedule, by which the node and the hub obtain scheduled and reoccurring time intervals to initiate frame transactions, in order to accommodate high or low duty cycle, periodic or quasi-periodic data traffic.

The scheduled-polling access method is based on the combination of scheduled access and polling access, by which the hub grants to a node and/or itself a scheduled reoccurring time intervals to initiate frame transactions, in order to accommodate high or low duty cycle, periodic or quasi-periodic data traffic.

The unscheduled access method is based on the combination of scheduled access and polling access, by which the hub grants to a node and/or to itself an unscheduled reoccurring time interval to initiate frame transactions, in order to accommodate high or low duty cycles, periodic or quasi-periodic data traffic.

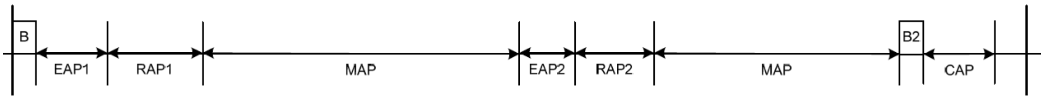
The improvised access method is based on improvised polling or posting access methods, whereby a hub grants to a node or to itself a polled or posted allocations to initiate one or more frame transactions, in order to accommodate improvised data traffic.

The contention access method is based on carrier sense multiple access with collision avoidance (CSMA/CA) or Slotted Aloha, whereby a node obtains a contended allocation in exclusive access phase (EAP), random access phase (RAP), or contention access phase (CAP), as depicted in Figure 2.3(a), to initiate one or more frame transactions, in order to accommodate unpredictable Uplink (From the node to the hub) data traffic. The IEEE 802.15.6 MAC frame format is shown in Figure 2.4.

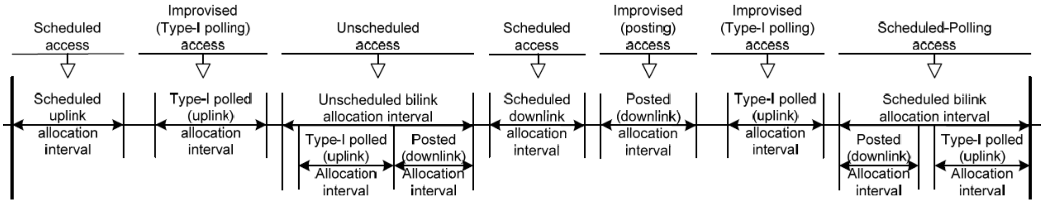
We focus in the next two Subsections 2.3.1 and 2.3.2 on the IEEE 802.15.6 CSMA/CA access method. We divide our state-of-the-art into two parts. The first part regards the related work to performance evaluation. In this part, we classify the performance evaluation studies of the IEEE 802.15.6 CSMA/CA access method into Markovian and non-Markovian analyses. The second part provides the related work to the enhancement of the IEEE 802.15.6 CSMA/CA access method in terms of backoff counter and contention window.

2.3.1 CSMA/CA performance evaluation: state of the art

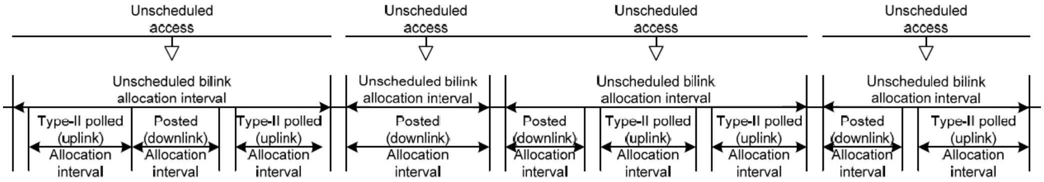
Several studies in the literature have been proposed to analyze and evaluate the performance of the IEEE 802.15.6 CSMA/CA access method in terms of WBAN requirements. Many of them are based on Markov chain models, which provide an accurate analysis of the protocol behavior compared to simulations that rely on predefined scenarios.



((A)) Beacon mode with superframes



((B)) Non-beacon mode with superframes



((C)) Non-beacon mode without superframes

FIGURE 2.3: Access modes of the IEEE 802.15.6 MAC protocol (Association et al., 2012).

In this subsection, we list the works which evaluated the performance of the IEEE 802.15.6 CSMA/CA access method, using Markovian and non-Markovian approaches.

Markovian analysis

S. Rashwand et al developed the first Markov chain-based analysis of the IEEE 802.15.6 CSMA/CA access method. In (Rashwand, Mišić, and Khazaei, 2011), the authors proposed a three-dimensional Markov chain (TDMC) to model the IEEE 802.15.6 CSMA/CA access method under saturation condition and error-prone channel. Then, they used the probability generating functions (PGFs) with the TDMC to compute the average time between two successive successful accesses to the medium and the normalized throughput for all user priorities (UPs). In (Rashwand and Misic, 2011), a TDMC model of the access method is presented under the non-saturation condition. Through simulation, they validated the analytical results, with regards to, the mean response time of the network. Both studies (Rashwand, Mišić, and Khazaei, 2011) and (Rashwand and Misic, 2011) were limited to the first exclusive and random access phases (EAP1 and RAP1). Although, the authors extended their studies in (Rashwand and MišIć, 2012) by considering the EAP1, RAP1, EAP2, RAP2, and type-I/II access phases. B. H. Jung et al. proposed in (Jung, Akbar, and Sung, 2012) a discrete-time Markov chain (DTMC) to evaluate the performance of the IEEE 802.15.6 CSMA/CA access method under non-saturation conditions. They evaluated the average throughput, energy consumption, and energy efficiency of nodes with different UPs. In (An et al., 2013), An et al. constructed a TDMC model

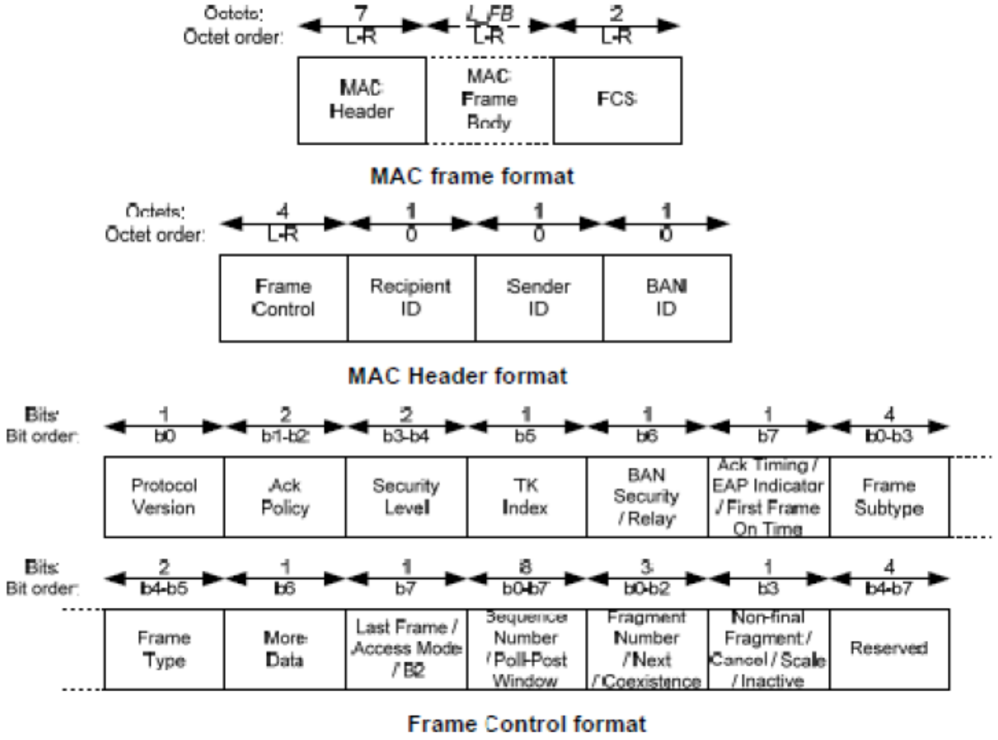


FIGURE 2.4: IEEE 802.15.6 MAC frame format including the MAC Header format and the Frame Control format (Association et al., 2012).

of the access method to analyze throughput, delay, and energy consumption, under saturation and non-saturation conditions. They assumed that collision only occurs in the transmission of the request to send (RTS) frames (the RTS mechanism is not used in the access method). C. Li et al designed in (Li et al., 2013) a Markov chain model to evaluate the performance of the IEEE 802.15.6 CSMA/CA access method in terms of normalized throughput and average access delay under saturation conditions. However, the work was limited to the assumption that the node always has enough time to complete a packet transaction in the access phases, and that the channel is ideal. Cavallari et al. (Cavallari and Buratti, 2014) presented an analytical model to evaluate the performance of the IEEE 802.15.6 CSMA/CA access method in terms of mean delay and probability of successful transmission. However, the model proposed did not take account of the collision. In (Bandyopadhyay et al., 2014), the authors analyzed the access method through TDMC. They modeled the backoff stage, backoff counter, and re-transmission counter, as stochastic parameters with different user priorities, but they did not model the backoff freezing. Bradai et al (Bradai, Fourati, and Kamoun, 2014) developed an analytical model in order to evaluate the performance of the IEEE 802.15.6 CSMA/CA access method in terms of mean response time and normalized throughput. The authors employed a probabilistic approach for modeling the backoff procedure in exclusive and random access phases and under saturation condition. In addition, they used a fine-tuning of the

EAPs and RAPs lengths to evaluate their effects on the performance of the IEEE 802.15.6 CSMA/CA access method. In (Rashwand, Mišić, and Mišić, 2015), a detailed TDMC model is proposed to investigate the performance of the IEEE 802.15.6 CSMA/CA access method under non-saturated condition and an error-prone channel. The model included a Geo/G/1 queuing sub-model of the node buffer, and all the user priorities. The authors proposed in (Shu et al., 2015) a TDMC to model the backoff procedure, and an M/G/1/K queuing system to describe the packet queues in the buffer under saturation condition. In (Khan et al., 2015) a DTMC model was developed to evaluate the performance of the IEEE 802.15.6 CSMA/CA access method under non-saturation conditions. In these works, the Markov chain models assumed the access probability and/or the packet arrival rate to be fixed, and the effect of unsuccessful transmissions due to busy channel or collision was not considered. Moreover, the models have not taken into account the time waiting for an acknowledgment after the packet transmission. The subsequent works have taken into account these problems. In (Sarkar et al., 2015), the authors designed a detailed DTMC model of the IEEE 802.15.6 CSMA/CA access method for non-ideal channel conditions, and immediate acknowledgement (I-ACK) policy. In (Kumar and Gupta, 2016), the authors developed a 4-tuple DTMC model that included the failure probability of the collision by distinctively modeling the acknowledgment (ACK) and the computational collision probability. Contrariwise, (Hiep, Kohno, et al., 2017) proposed the Markov chain Monte Carlo (MCMC) method to analyze the performance of the IEEE 802.15.6 CSMA/CA access method, because the authors assume that the calculation of access probability while considering BER/PER is complicated. Also in (Khan, Ullah, and Kim, 2017), the authors did not consider the ACK timeout state. As well, (Benmansour et al., 2020) proposed a general and accurate analytical model, but the model did not include the Ack frame failing transmission.

Non-Markovian analysis

S.Ullah et al proposed in (Ullah and Kwak, 2011; Ullah, Chen, and Kwak, 2012) the first non-Markovian analysis of the IEEE 802.15.6 CSMA/CA access method in terms of the maximum throughput and minimum delay bounds for different data rates and frequency bands. However, the studies were limited to the ideal channel with no transmission errors. In addition, (Ullah, Chen, and Kwak, 2012) set the backoff counter in a sample of an integer random variable uniformly distributed over the interval $[0, CWmin]$, which is conflicting with the IEEE 802.15.6 CSMA/CA access method structure. In (Panunzio et al., 2013), the authors implemented the IEEE 802.15.6 CSMA/CA access method just during the CAP access phase of the IEEE 802.15.6 superframe structure. Through simulation, the authors (Toumanari, Latif, et al., 2014) analyzed the performance of the IEEE 802.15.6 CSMA/CA access method in terms of packets received per node, energy consumption, and latency. In (Fourati et al., 2015), the authors allocated all the superframe as only one access phase period to establish the performance evaluation of the IEEE 802.15.6 CSMA/CA access method. In (Ullah and Tovar, 2015) a simple and accurate analytical model is developed to compute the normalized throughput, energy consumption, and delay of the IEEE 802.15.6 CSMA/CA access method. The model assumed saturated and lossy channel conditions, but the study was used only for UP0 and UP2. Zhang, Moungla, and Mehaoua, 2015 analyzed theoretically the delay of IEEE 802.15.6 CSMA/CA access method under duty cycle. Then, they simulated the delay as a function of the sleep and active time. In (Benmansour, Ahmed, and Moussaoui, 2016), the authors evaluated the performance of the IEEE 802.15.6 CSMA/CA access method in terms of energy consumption, latency, and packets delivery rate. In (Frigo and Giorgi, 2017), the authors implemented a case study of the IEEE 802.15.6 CSMA/CA access method to evaluate the effect of the missing packets on the resulting quality of service. The authors evaluated in (Singh and Gupta, 2018) the performance of the IEEE 802.15.6 CSMA/CA access method for moving and stationary body scenarios in terms of total energy consumption, total delay, packet delivery ratio, and throughput.

2.3.2 CSMA/CA performance enhancement: state of the art

Several improvements to the IEEE 802.15.6 CSMA/CA access method have been proposed. In this section, we present the works closest to our tackled problem.

In (Shankar and Jacob, 2016), the authors used a non-cooperative game theoretical framework to improve the performance of IEEE 802.15.6 MAC by controlling the contention window size. The proposed design aims to compute the optimal channel access probability of each node. The calculated probability is translated to an optimal contention window size. The results presented the improvement performances of the WBAN in terms of throughput and delay. The authors limited this study to nodes with the same UP. The authors in (Fourati, Idoudi, and Saidane, 2016) modified the backoff counter process for all user priorities during transmissions and even-numbered re-transmissions. However, they missed the definition of the backoff counter selection process for odd-numbered re-transmissions. In (Khan et al., 2017), the authors proposed a prioritized Fibonacci backoff (PFB) scheme. This efficient algorithm allows after each collision a smooth and gradual increase of contention window size compared to the algorithm used in IEEE 802.15.6. The analytical and simulation results proved that this algorithm improved the performance of WBANs in terms of waiting time, delay, throughput, and energy consumption. However, the contention window size rule was not defined. In (Fourati, Idoudi, and Saidane, 2018), a new dynamic backoff that modified the backoff counter value during the re-transmission process is proposed. It is related to all priorities except UP2 and UP4. Based on this work, the contention window bounds have the same value for UP2 and UP4, which leads to more collisions in the case of nodes with the same UP4 or UP2. As well, contention window bounds exceed the IEEE 802.15.6 contention window bounds many times in the re-transmissions cases. The authors in (Saboor et al., 2018) sorted the nodes according to their UPs, then they assign to each node a unique backoff that is equal to the ordinal number of the node. However, they did not define how they sorted the nodes of the same UP. The authors in (Saboor et al., 2020) proposed a non-overlapping backoff algorithm that improved the performance of the WBAN in terms of throughput and latency. But, they did not define how they selected the window limit (LM). In (Adnan et al., 2020), the authors proposed to extend the IEEE 802.15.6 $CWmin$ value of each UP to prevent homogeneous collisions (collision of nodes with the same UP). The extension aims to add the number of nodes that have the same UP to the IEEE 802.15.6 $CWmin$ value. Yet, the delay increases for emergent data, especially, in the case of the network growth.

The work of this thesis is a complement to the aforementioned studies, whereby we evaluate and improve the performance of the IEEE 802.15.6 MAC protocol. We propose in our investigation to use a formal verification method.

2.4 Formal verification

With the growing up of the hardware and software systems in terms of scale and functionality, the systems errors increase and may cause catastrophic loss of time, money, and human life. The only way to ensure the reliability of these systems is through formal verification based on formal methods. These methods are not the panacea: they can not guarantee the correctness of the systems. However, they can increase the understanding of the systems by revealing ambiguities, incompletenesses, and inconsistencies that can not be detected by program testing (Clarke and Wing, 1996; Emerson, 2008; Baier, 2008). Thereafter, we will give a brief definition of the formal methods, the formal methods tools, and the model checker UPPAAL-SMC.

2.4.1 Formal methods

Formal methods are considered as the applied mathematics for modeling and analyzing software and hardware systems (Baier, 2008). The verification problem that the formal methods should resolve is defined in (Emerson, 2008) as follows: *"given program M and specification h determine whether or not the behavior of M meets the specification h"*. The formal methods view the system as mathematical objects with well-determined behavior. This makes it possible to specify what constitutes the intended behavior using mathematical logic, then proving that the behavior of the system meets its specification. We distinguish two well established formal methods: theorem proving and model-checking (Clarke and Wing, 1996).

Theorem proving. Is a method where both the system and its specifications (properties) are expressed as formulas in mathematical logic. Theorem proving is the process of finding a proof of a property, while proofs constructed manually. This interaction with human generates error-prone (Clarke and Wing, 1996).

Model-checking. Is an automated method for verifying the concurrent finite state systems. It is based on the construction of a model of the system and verifying if the specification of the system holds in the model or not.

model-checking structure. the model-checking structure is defined in (Emerson, 2008) as follows: *"let M be a Kripke structure (i.e., state transition graph). Let f be a formula of temporal logic (i.e., the specification). Find all states s of M such that* $M, s \models f$*; verifying if the temporal formula f was true in the kripke structure M."*

Temporal logic. The temporal logic is an extension of classical logic where operators relating to time were added (Fisher, 2011). Temporal logic has played a central role in the success of model-checking, because of its high ability and flexibility to specify the system properties such as safety (i.e., something bad will never happen), reachability (i.e., it is possible to end up in a deadlock state), and liveness (i.e., something good will eventually happen) (Baier, 2008; Behrmann, David, and Larsen, 2004). There are different types of temporal logic (Mouradian, 2013) such as linear temporal logic (LTL) that reasons about execution paths, computational tree logic (CTL) that reasons on execution trees, LTL and CTL derivatives which explicitly take into account time and probability (PLTL, TLTL, PCTL, TCTL, PTCTL), CTL*, and μ-calculus.

Formal semantics. The formal semantics of temporal logic formulae are defined in (Emerson, 2008) as follows: *"The formal semantics of temporal logic formulae are defined with respect to a (Kripke) structure $M = (S, S0, R, L)$ where S is a set of states, $S0$ comprises the initial states, $R \subseteq S \times S$ is a total binary relation, and L is a labeling of states with atomic facts (propositions) true there. An LTL formula h such as FP is defined over path $x = t0, t1, t2...$ through M by the rule $M, x \models FP$ iff $\exists i\ 0\ P \in L(ti)$. Similarly a CTL formula f such as EGP holds of a state $t0$, denoted $M, t0 \models EGP$, iff there exists a path $x = t0, t1, t2, ...$ in M such that $\forall i\ 0\ P \in L(ti)$. For LTL h, we define $M \models h$ iff for all paths x starting in $S0, M, x \models h$. For CTL formula f, we define $M \models f$ iff for each $s \in S0$, $M, s \models f$. A structure (e.g., structure M) is also known as a state graph or state transition graph or transition system."*

State transition graph. When the system is a finite state, the use of finite automata led to the effective construction and decision procedure for automatically modeling system behavior (Alur and Dill, n.d.). Classical automata could not model the time, consequently, timed automata are introduced as a formalism to model the behavior of real-time systems (Alur and Madhusudan, 2004).

Timed automata. A timed automaton as defined in (Alur and Dill, n.d.; Alur and Madhusudan, 2004) is a finite automaton with a finite set of clocks. The vertices of the automaton are called locations, and edges are called switches.

Formal definition. generally, the definition of formal language is a set of finite words over some given finite alphabet (Alur and Dill, n.d.). So formally, a timed automaton A over an alphabet $\sum$ is defined as follows:

A timed automaton A over an alphabet $\sum$ is a tuple $\langle V, V^0, V^F, X, E \rangle$, where:

- *V is a finite set of locations,*
- *$V^0 \subseteq V$ is a set of initial locations,*
- *$V^F \subseteq V$ is a set of final locations,*
- *X is a finite set of clocks,*
- *$E \subseteq V \times \sum^{\epsilon} \times \Phi(X) \times 2^X \times V$ is a set of switches. A switch $\langle s, a, g, \lambda, s' \rangle$ represents an edge from location s to location s' on symbol a. The guard g is a clock constraint over X that specifies when the switch is enabled, and the update $\lambda \subseteq X$ gives the clocks to be reset to 0 with this switch.*

Compared to the theorem proving, the model-checking has several advantages that are detailed in (Clarke, 2008). Some of these advantages are: no proofs, fast, diagnostic counterexamples, and the use of temporal logics can easily express many properties of the concurrent systems. The only and major problem of model-checking is the state-explosion. The model-checking has been used primarily in the verification of the synchronization protocols, and it is considered as a useful method for the analysis and the evaluation of the communication protocols.

2.4.2 Formal methods tools

There are several tools developed for formal verification which are detailed in (Wang, 2004), while the model-checking tools (model-checkers) are our interest. The most popular model-checkers are: PRISM (Kwiatkowska, Norman, and Parker, 2002) is a standard for probabilistic symbolic model-checker that allows working with Markov chains. Hytech (Henzinger, Ho, and Wong-Toi, 1997) is an ICTL model-checker for the linear hybrid systems. Kronos (Bozga et al., 1998) is a model-checker based on timed automata and TCTL. UPPAAL (Bengtsson et al., 1995) is a model-checker for real-time systems, that is based on CTL and timed automata extended with integer variables, structured data types, and channel synchronization. It is the best-known toolbox for the verification of the communication protocols. It provides many extensions such us UPPAAL-CORA (Larsen et al., 2001), UPPAAL-TIGA (Behrmann et al., 2007), UPPAAL-STRATEGO (David et al., 2015), and UPPAAL-SMC (David et al., 2011a; David et al., 2011b).

Adequate model checker tool for WBAN

The WBAN is considered as a stochastic environment, where the prediction of the time when the physiological parameters change their values is non-deterministic. The problem is how to model and evaluate the behavior of the access methods under the stochastic nature of the WBAN. The statistical model-checking toolset UPPAAL-SMC has the ability to provide a stochastic interpretation of the stochastic behavior of complex and real-time systems, such as WBANs, and it is based on the statistical model-checking (SMC).

2.4.3 UPPAAL-SMC

The UPPAAL-SMC (David et al., 2015) is an alternative to the timed automata limits. The timed automata formalism is not flexible and expressive enough to model the behavior of complex cyber-physical systems. The UPPAAL-SMC formalism is based on a stochastic interpretation and an extension of timed automata formalism used in UPPAAL classical version (Bengtsson et al., 1995). Thus, generates stochastic timed automata (STAs). The stochastic interpretation replaces the non-deterministic choices between multiples enabled transitions, by using probabilistic choices, that can the user-defined or not. In addition to the non-deterministic choices of time delays that are defined by the probability distributions, which applies uniform distributions for bounded delays and exponential distributions for unbounded delays. A model in UPPAAL-SMC consists of a network of interacting component STAs. The component STAs communicate via broadcast channels and shared variables to generate networks of stochastic timed automata (NSTAs). To specify properties over NSTAs, UPPAAL-SMC uses a weighted extension of the temporal logic MITL (metric interval temporal logic) (Alur, Feder, and Henzinger, 1996). And, for an efficient analysis of probabilistic performance properties, UPPAAL-SMC works with statistical model-checking (SMC) (Clarke and Zuliani, 2011) which is considered as an alternative to avoid the state-explosion of the model. The SMC uses the Monte Carlo simulation to respond to the quantitative questions (i.e., Probability Estimation), and it uses Sequential Hypothesis Testing to respond to the qualitative questions (i.e., Hypothesis Testing and Probability Comparison). Additionally, UPPAAL-SMC provides the Simulation of the system behavior and the Evaluation of the expected value of the max or the min expression. The properties syntax is as follows:

1. The Probability Estimation:
   $Pr[bound](\psi)$.
   The formula ψ *can be* $<>q$ *or* $[\,]q$*, where* q *is a state predicate. The bound is a time bound.*

2. The Hypothesis Testing:
   $Pr[bound](\psi) >= p_0$.

3. The Probability Comparison:
   $Pr[bound_1](\psi_1) >= Pr[bound_2](\psi_2)$.

4. The Simulation:
   simulate N $[<= bound]$ $\{E_1,...,E_k\}$.
   Where, N is a natural number that indicates the number of simulations to be performed, bound is a time bound in the simulation, and $E_1,...,E_k$ *are the k state-based expressions that are to be monitored and visualized.*

5. The Evaluation of the expected values of min or max:
   $E[bound; N](min: expr)$ or $E[bound; N](max: expr)$.
   Where, $expr$ *is the expression to evaluate.*

We synthesize that in this chapter, we stated the definition, components, communication architecture, requirements and the existing MAC protocols of WBANs. In addition, we listed the studies that evaluated the performance of the IEEE 802.15.6 CSMA/CA access method. Then, we finished the chapter by selecting the formal method toolset adequate for WBANs.

Chapter 3

Posting Access Method: Scalability Validation

The IEEE 802.15.6 MAC protocol access is divided into five classes that are scheduled, scheduled-polling, unscheduled, improvised, and contention, as defined in Section 2.3. Accordingly, the posting is the only access method that is used by the hub to transmit its frames in scheduled, scheduled-polling, unscheduled, and improvised access classes.

Posting is the most important access method for the hub. This latter uses it to grant itself a posted allocation for initiating one or more frame transactions. A posted allocation is a downlink allocation time interval, during which the hub can service and transmit unexpected or extra management and data traffic to the node. For example, it is used in the case of network management needs, data rate variations, and channel impairments.

Due to the important role of the hub in the WBAN, as a controller and monitor device, evaluating the scalability of its posting access method is important. Scalability represents the ability of the network to continue to operate with the same performance despite the addition of other nodes (Movassaghi et al., (2014)). Validating this property allows the validation of the posting access method and, therefore, the performance of the WBAN.

In this chapter, we propose to use the statistical model checking toolset UPPAAL-SMC, as defined in Subsection 2.4.3, to investigate the posting access method under the WBANs stochastic environment, as depicted in Figure 3.1. Based on UPPAAL-SMC, we model and evaluate the behavior of the posting access method in terms of scalability. This is the first study of the posting access method through UPPAAL-SMC in our best knowledge. We first use the stochastic timed automata (STA) formalism provided by UPPAAL-SMC to construct a detailed model of this behavior. Then we use the metric interval temporal logic (MITL) specifications adopted by UPPAAL-SMC to evaluate the scalability of this behavior. In addition to evaluate the scalability according to the energy consumed by the hub and the throughput, which are, respectively, the dominant problem and the key performance properties that we should validate for WBAN. We should, also, evaluate the number of the posted allocation time intervals of the hub. This property shows the ability of the hub to still communicate with the nodes despite the growth of the network density.

The rest of this chapter is organized as follows: the next Section 3.1 describes the behavior of the posting access method. Section 3.2 provides the posting access

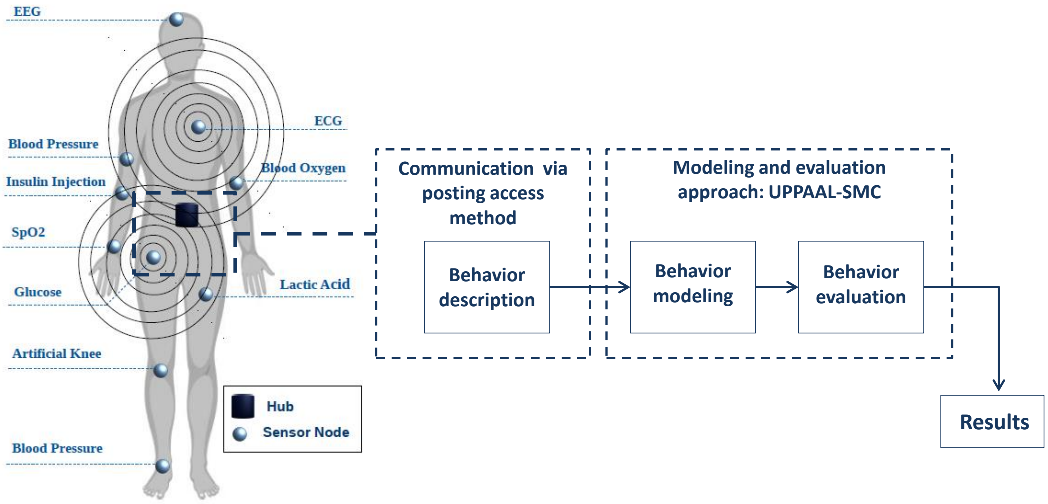


FIGURE 3.1: The WBAN illustration and the used approach for the communication method modeling and evaluation. EEG: ElectroEncephaloGraph. ECG: ElectroCardioGraph. SpO2: blood oxygen saturation level.

method behavior modeling. Section 3.3 presents the posting access method behavior evaluation. Section 3.4 presents the chapter's conclusion.

3.1 Posting access method: behavior description

In this section, we describe the behavior of the posting access method before, within, and after the posted allocation time interval.

3.1.1 Before the posted allocation time interval

Based on the posting access method, to grant to itself a posted allocation time interval, the hub sends to the node a poll frame, as depicted in Figure 3.2. This latter is a control frame addressed to the node to inform it about a future post. A post is a management or data frame sent by the hub to the node within a posted allocation time interval. While granting the posted allocation time interval, the hub can start sending posts after a pre-determined time.

3.1.2 Within the posted allocation time interval

When the posted allocation time interval starts, the hub can transmit one or more new frames and it can retransmit one or more old frames. These frames are separated by a short inter-frame spacing (*pSIFS*) time. The hub transmits the frame with a required immediate (I-ACK) or block (B-ACK) acknowledgement frame and with the more data (M) and the last frame (L) fields of the MAC frame header, as depicted in Figure 2.4. The values of these fields can be presented according to the cases as follows :

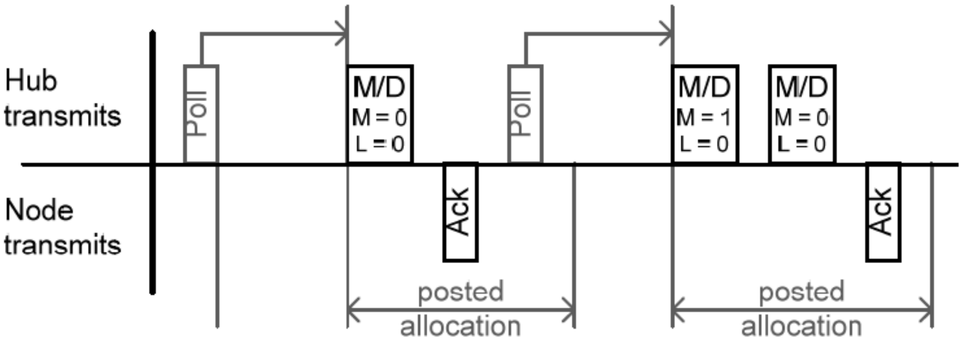


FIGURE 3.2: Posting access method illustration: the future posts transactions (Association et al., 2012).

1. Case 1, with $M = 0$ and $L = 0$: it means that no frames are waiting for transmission. Other than probable retransmission of the last frame in the current posted allocation time interval. That one is most likely due to the no reception of the required acknowledgement frame. Otherwise, the hub should relinquish and reclaim the posted allocation time interval if it has received the required acknowledgement frame from the node.

2. Case 2, with $M = 1$ and $L = 0$: it means that one or more frames are waiting for transmission or retransmission after a *pSIFS* time in the current posted allocation time interval.

3. Case 3, with $M = 0$ and $L = 1$: it means that no frames are waiting for transmission. Other than the probable retransmission of the last frame in the next posted allocation time interval. That one is most likely due to the no reception of the required acknowledgement frame. As well, is due to not having enough time remaining in the current posted allocation time interval for completing another frame transaction plus an appropriate guard time. Thus, the hub should relinquish and reclaim the current posted allocation time interval.

4. Case 4, with $M = 1$ and $L = 1$: it means that one or more frames are waiting for transmission or retransmission in the next posted allocation time interval. That one is most likely due to not enough time remaining in the current posted allocation time interval for completing another frame transaction plus an appropriate guard time. In this case, the hub should relinquish and reclaim the current posted allocation time interval.

After sending the required acknowledgement frame to the hub, the node behaves according to the cases defined above. For the first case, it should be ready to receive the retransmission of the last frame after a *pSIFS* time. As well, it should relinquish the current posted allocation time interval after a time out (*mTimeOut*) if at this time it has not received it. As for the second case, it should be ready to receive the transmission or the retransmission of one or more frames in the current posted allocation time interval. While for the third and fourth cases, it should relinquish the current posted allocation time interval.

3.1.3 After the posted allocation time interval

After the end of the posted allocation time interval or after reclaiming it, the hub can send to the node a poll frame conveying an immediate or a future new posted allocation time interval, extending the remaining or the existing one if there are other frames to transmit. Moreover, it can cancel the future posted allocation time interval by sending a poll frame to the node before the start of it.

Thereafter, we will model the detailed communication between the hub and the nodes through the posting access method and within the stochastic environment of WBAN.

3.2 Posting access method: behavior modeling

In this section, based on the STA formalism of the UPPAAL-SMC model-checker, we model the whole behavior of the posting access method before, within, and after the posted allocation time interval. The resulting model is a network of stochastic timed automata (NSTA) that is composed of a couple of two templates, as depicted in Figure 3.5.

We mention in Table 3.1 and Figure 3.6 the intervals of the random functions, the values of the parameters used in this model, and the illustration of these parameters value determination.

3.2.1 Behavior modeling of the hub and the nodes before the posted allocation

Consider the Hub template, as depicted in Figure 3.3. It starts with the stochastic interpretation of its non-deterministic choice between allocating time intervals for itself or to the node. Indeed, according to the data sensed by the node or the data received by itself, the hub determines its choice. The node allocated time interval starts at the location *ImmNodeAlloc*. The hub allocated time interval (i.e., the posted allocation time interval) starts after an (X) time-units. The X is selected randomly through the random function *rand* $(e : rand)$. The posted allocation is considered as a future allocation compared to the allocation of the node. This latter is considered as an immediate or future allocation. In this section, we model the allocation of the node as an immediate allocation.

To inform the node about its allocated time interval, the hub sends to it a poll frame. In this case, it sends the signals $(IP[id]!)$ and $(EP[id]!)$. These signals indicating, respectively, the start and the end of the poll frame. While in the case of the hub allocated time interval, it sends to the node the signals $(FP[id]!)$ and $(EP[id]!)$. The same as the first signals, these signals indicating, respectively, the start and the end of the poll frame.

We model the communication between the hub and the nodes of the network by a random selection of a node (i) from the network to communicate with the hub. We use the function *randid* $(eid : randid)$ for this random selection. Then, we put in it the variable $(id)(id = eid)$. This latter represents the identifier of the selected node. As

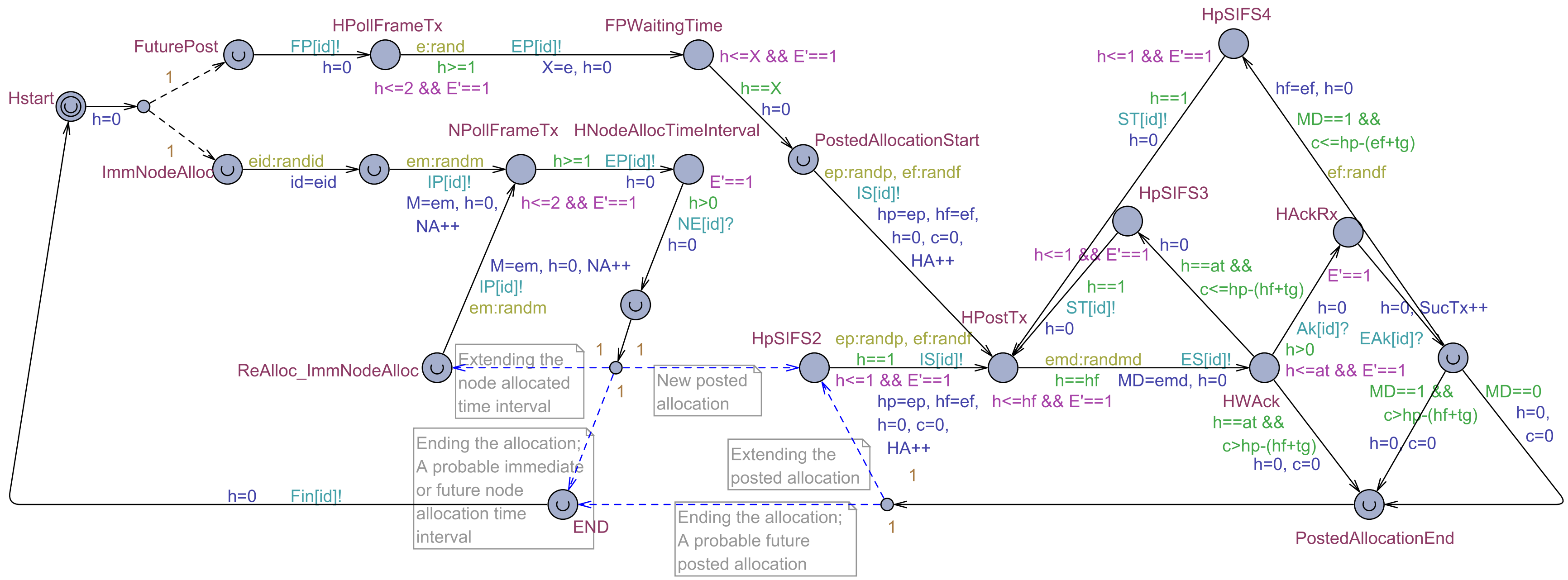


FIGURE 3.3: Hub template.

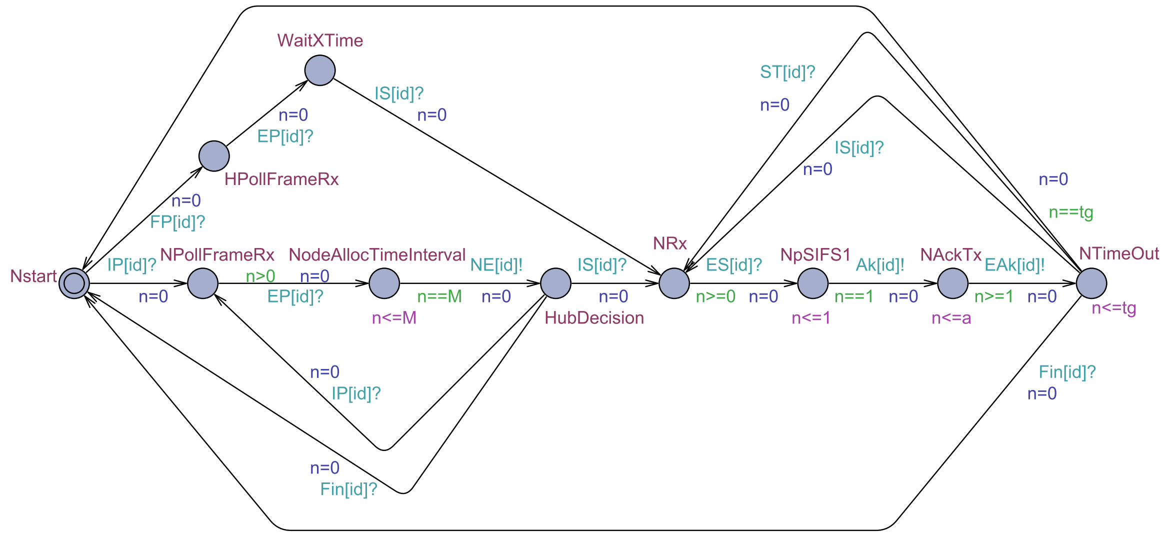


FIGURE 3.4: Node template.

FIGURE 3.5: NSTA model of the posting access method.

well, we define the time interval (M) of the node allocation randomly through the function *randm* ($em : randm$).

We define the posted allocation time interval and the required time of the frame transmission by a random selection: ($ep : randp$) represents the random selection of the posted allocation time interval, and ($ef : randf$) represents the random selection of the frame transmission time. Then, we put them in the variables ($hp = ep$) and ($hf = ef$), respectively. The variable (MD) used in the Hub template, indicates to the Node template if the hub has more data to transmit ($MD == 1$) or not ($MD == 0$). This variable is determined randomly by the function *randmd* ($emd : randmd$, $MD = emd$). The clock (c) is used in the Hub template to compute the current time of the posted allocation time interval. It starts after the locations *PostedAllocationStart* or *HpSIFS2* and resets at the end of the posted allocation time interval, in the location *PostedAllocationEnd*. The clock (h) is used locally to compute the time in the locations.

3.2.2 Behavior modeling of the hub and the nodes within the posted allocation

Once the posted allocation time interval starts (i.e., immediately after the locations *PostedAllocationStart* or *HpSIFS2*), the Hub starts the transmission of its frame by sending to the Node the synchronization signal ($IS[id]!$). After the transmission time of the frame ($h == hf$), the Hub sends to the Node the synchronization signal ($ES[id]!$) indicating the end of the frame transmission. Then, it moves to the location *HWAck* waiting for the reception of the acknowledgement frame:

1. If the Hub receives from the Node the synchronization signals ($Ak[id]?$) and ($EAk[id]?$) that are indicating, respectively, the start and the end of the immediate acknowledgement frame transmission, it moves to:
    (a) The transmission of a new frame with new frame transmission time ($ef : randf$), if it has more data to transmit ($MD == 1$) and if there is enough time in its posted allocation time interval ($c \leq hp - (ef + tg)$). This transmission will start after staying in the location *HpSIFS4* for the pSIFS time $h == 1$. The guard ($c \leq hp - (ef + tg)$) represents the L state (in this case $L = 0$) and its value is determined as depicted in Figure 3.6.
    (b) The location *PostedAllocationEnd*, if it has more data to transmit ($MD == 1$), but it has no more time to complete its frame transaction ($c > hp - (hf + tg)$, in this case $L = 1$).
    (c) The location *PostedAllocationEnd* if it has no more data to transmit ($MD == 0$). The Hub resets the clock c before moving to the location *PostedAllocationEnd*, which means the relinquishment of the posted allocation time interval.
2. If the Hub has not received during ($h == at$) time-units the synchronization signal ($Ak[id]?$), it should retransmit, after staying in the location HpSIFS for ($h == 1$), its last frame if it has enough time in its current posted allocation ($c \leq hp - (hf + tg)$). Otherwise, it resets the clock c and moves to the location *PostedAllocationEnd*.

Consider the Node template, as depicted in Figure 3.4. After receiving from the Hub the synchronization signals ($IS[id]?$) and ($ES[id]?$), the Node waits for a *pSIFS* time ($n == 1$) in the location *NpSIFS1*. Then, it moves to the transmission of the acknowledgement frame, which starts and ends after sending to the Hub the synchronization signals ($Ak[id]!$) and ($EAk[id]!$), respectively. After that, the Node moves to the location *NTimeOut*, where it waits for (tg) time-units the reception of the signals ($IS[id]?$), ($ST[id]?$), or ($Fin?$). The value of tg is determined as depicted in Figure 3.6. If at this time it has not received any signal from the Hub (e.g., the hub is broken down), the Node relinquishes the current allocation time interval by returning to the location *Nstart*. The signal ($ST[id]?$) indicates the transmission of a new frame or the retransmission of the last frame. The signal ($IS[id]?$) indicates the start of a newly posted allocation time interval and the start of the first Post. While the signal ($Fin[id]?$) indicates the end of the allocation time interval of the hub.

The acknowledgement frame: missing situation we consider that the hub and the nodes are connected. As mentioned in Figure 3.2, the hub sends to the node the poll frame without a required acknowledgement frame. The problem is that in the case of the transmission loss of the poll frame, the hub can not synchronize with the node when the posted allocation starts. Therefore, this situation allows the data frame transmission loss. We suppose that the posting access method treats this situation through the requirement of an acknowledgement frame transmitted with the data frame, as explained before in Section 3.1. However, the posting access method has not treated the case of the transmission loss of this acknowledgement frame. To prevent that, the hub stays blocked until the end of the posted allocation time interval waiting for the acknowledgement frame, we proposed in our model a bounded time (at) during with the Hub automaton can stay in the location *HWAck*. Its value is determined as depicted in Figure 3.6.

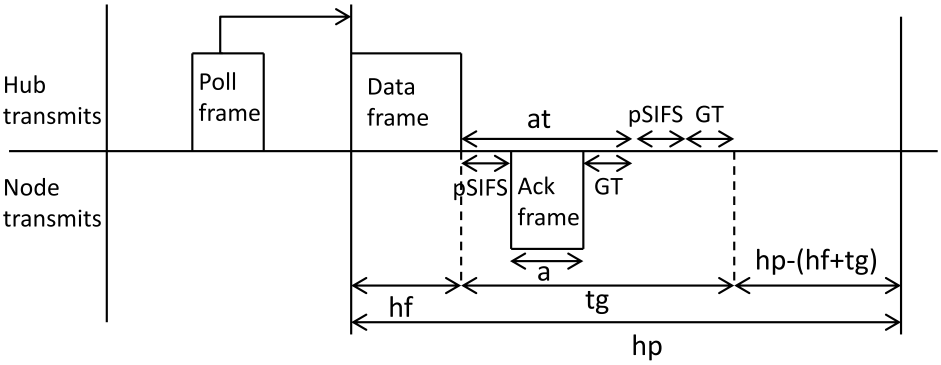


FIGURE 3.6: Illustration of the parameters value determination. GT: Guard Time. Ack: acknowledgement.

3.2.3 Behavior modeling of the hub and the nodes after the posted allocation

The blue lines represent the Hub decision after the end of the allocation time interval of itself or for the node. After the end of the allocation time interval, we use another stochastic interpretation, with the same probability weight (i.e., the probability weight as called in UPPAAL-SMC $Pw = 1$), to model the non-deterministic choice of the hub between extending the existing allocation and granting a probably immediate or a future new allocation time interval.

Based on this accurate behavior model of the posting access method and according to the values of the parameters used in this model, we will evaluate in the next section, the performance of this access method.

TABLE 3.1: Parameters values and random functions intervals.

$rand$	$[5, 10]$	$randp$	$[10, 25]$
$randf$	$[3, 5]$	$randm$	$[10, 25]$
$randmd$	$[0, 1]$	a	3
tg	7	at	5
$pSIFS$	1	GT	1

3.3 Posting access method: behavior evaluation

In this section, to evaluate the scalability of the posting access method, we use the following property:

- The evaluation of the expected values of max:

$$E[bound; N](max : expr) \tag{3.1}$$

  Where $bound$ is a time-bound in the evaluation, N is the number of runs, and $expr$ is the expression to evaluate.

In a network of nodes ranging from 4 to 64 and through $N = 10000$ runs of stochastic scenarios generated by UPPAAL-SMC, we evaluate the scalability. This latter, we evaluate it in terms of the number of the allocated time intervals of the hub and nodes. As well, the energy consumed and the successful transmitted frames by the hub during a determined period of time.

In the experiments, we use three networks and three periods of time ($T1$, $T2$, and $T3$) to evaluate and visualize the scalability of the posting access method. The first network is composed of one hub and 4 nodes. The second network is composed of one hub and 16 nodes. As for the third network is composed of one hub and 64 nodes. Moreover furthermore, the first period of time $T1 = 3600$ time-units, the second period of time $T2 = 7200$ time-units, and the third period of time $T3 = 10800$ time-units.

3.3.1 Allocated time intervals

Using Equation 3.1, we evaluate the average of the maximum number of allocated time intervals of the hub and the nodes within the three networks and during the three periods of time:

$$E[<= T; N](max : Hub.HA) \tag{3.2}$$

$$E[<= T; N](max : Hub.NA) \tag{3.3}$$

These formulae compute, in the interval of time T (i.e., the T can be $T1$, $T2$, or $T3$) and using N runs, the average of the maximum value of the counters (HA) and (NA).

In our NSTA model, as depicted in Figure 3.5, the Hub template uses the HA and NA counters to compute the number of allocated time intervals of the hub and the nodes, respectively. The Hub automaton increments the counter ($HA++$) when the posted allocation time interval starts. As well, it increments the counter ($NA++$) when the node allocated time interval starts.

UPPAAL-SMC estimates the averages of Equations 3.2 and 3.3 to be in the confidence intervals, as depicted in Tables 3.2 and 3.3, respectively. As well, Figures 3.7 and 3.8 present the visualization of the results for the hub and the nodes, respectively. The results show that within the three networks, the hub and the nodes retain the same number of the allocated time intervals during each period of time. Along with this, we remark that the hub allocates the double of the time intervals number compared to the nodes.

TABLE 3.2: Confidence intervals of the estimated averages of the maximum numbers of allocated time intervals for the hub.

Parameter evaluated: HA			
T	4 Nodes	16 Nodes	64 Nodes
$T1$	161.860 ± 0.248666	161.857 ± 0.249261	161.824 ± 0.246545
$T2$	323.919 ± 0.347292	323.716 ± 0.347743	323.389 ± 0.351441
$T3$	485.783 ± 0.431237	485.471 ± 0.433604	485.899 ± 0.430501

3.3.2 Energy consumption

Using Equation 3.1, we evaluate the average of the maximum value of the energy consumed by the hub within the three networks and during the three periods of time:

$$E[<= T; N](max : Hub.E) \tag{3.4}$$

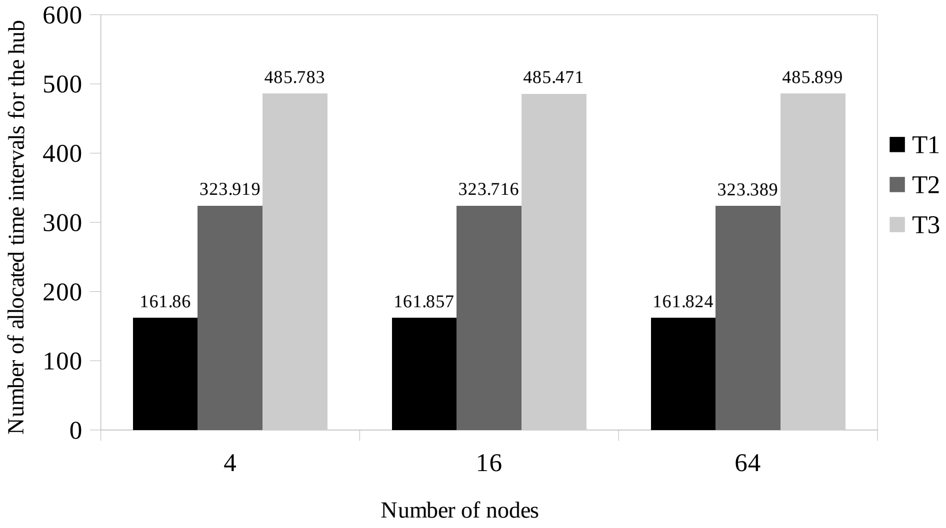


FIGURE 3.7: Averages of the maximum numbers of allocated time intervals for the hub within three networks and during three periods of time.

TABLE 3.3: Confidence intervals of the estimated averages of the maximum numbers of allocated time intervals for the nodes.

Parameter evaluated: NA			
T	4 Nodes	16 Nodes	64 Nodes
$T1$	81.2289 ± 0.163605	81.3295 ± 0.163182	81.4821 ± 0.162648
$T2$	162.254 ± 0.23184	162.237 ± 0.231811	162.305 ± 0.229111
$T3$	243.392 ± 0.285667	243.014 ± 0.285128	243.268 ± 0.281951

This formula computes, in the interval of time T (i.e., the T can be $T1$, $T2$, or $T3$) and using N runs, the average of the maximum value of the variable (E).

In our NSTA model, as depicted in Figure 3.5, the Hub template uses the variable E. This latter computes the energy consumed proportionally to the time spent by the hub when it passes by the locations that have ($E == 1$).

UPPAAL-SMC estimates the averages of Equation 3.4 to be in the confidence intervals, as depicted in Table 3.4. As well, Figure 3.9 presents the visualization of the results. These latter show that within the three networks, the hub retains the same value of the energy consumed during each period of time.

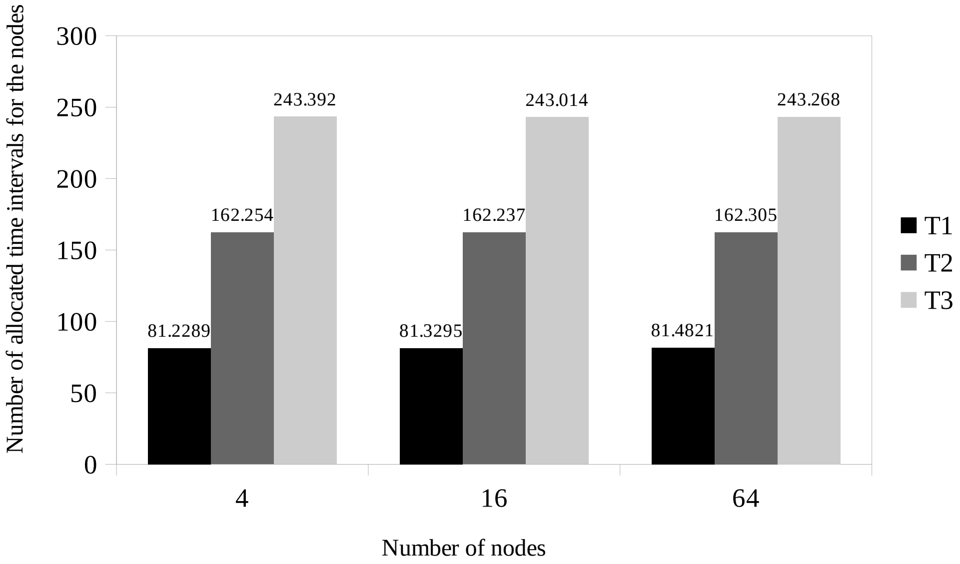


FIGURE 3.8: Averages of the maximum numbers of allocated time intervals for the nodes within three networks and during three periods of time.

TABLE 3.4: Confidence intervals of the estimated averages of the maximum values of the energy consumed by the hub.

Parameter evaluated: E			
T	4 Nodes	16 Nodes	64 Nodes
$T1$	3595.17 ± 0.107094	3595.17 ± 0.105837	3595.10 ± 0.107957
$T2$	7195.17 ± 0.106899	7195.15 ± 0.107162	7195.21 ± 0.105604
$T3$	10795.2 ± 0.106891	10795.2 ± 0.106597	10795.2 ± 0.105469

3.3.3 Throughput

Using Equation 3.1, we evaluate the average of the maximum number of the successful transmitted frames by the hub within the three networks and during the three periods of time:

$$E[<= T; N](max : Hub.SucTx) \tag{3.5}$$

This formula computes, in the interval of time T (i.e., the T can be $T1$, $T2$, or $T3$) and using N runs, the average of the maximum number of the counter ($SucTx$).

In our NSTA model, as depicted in Figure 3.5, the Hub template uses the counter $SucTx$ to compute the number of successful transmitted frames by the hub to the nodes. The Hub automaton increments the counter ($SucTx++$) when it receives

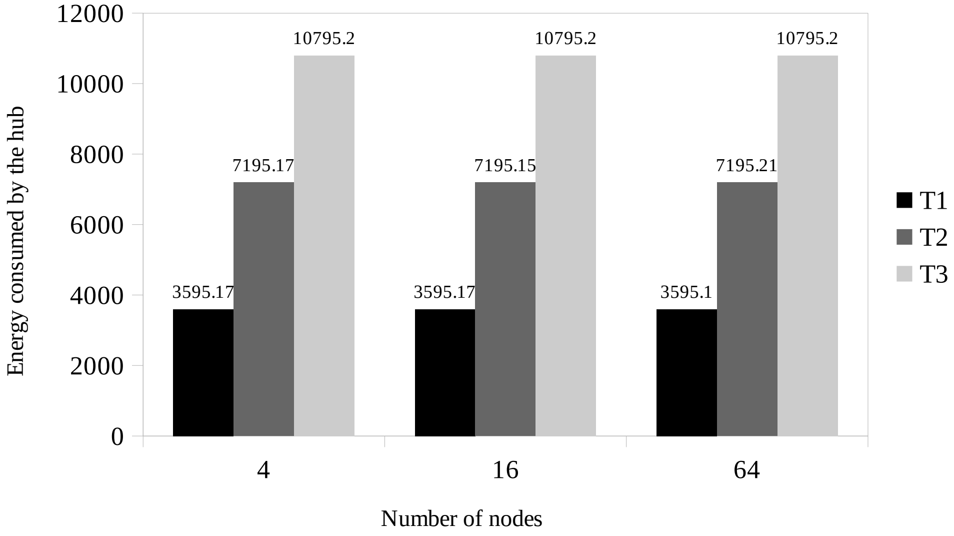


FIGURE 3.9: Averages of the maximum values of the energy consumed by the hub within three networks and during three periods of time.

the acknowledgement frame from the node.

UPPAAL-SMC estimates the average of Equation 4.4 to be in the confidence intervals, as depicted in Table 3.5. As well, Figure 3.10 presents the visualization of the results. These latter show that within the three networks, the hub almost retains the same number of throughput during each period of time.

TABLE 3.5: Confidence intervals of the estimated averages of the maximum numbers of successful transmitted frames by the hub.

Parameter evaluated: $SucTx$			
T	4 Nodes	16 Nodes	64 Nodes
$T1$	203.968 ± 0.31096	203.873 ± 0.312695	203.880 ± 0.312903
$T2$	408.322 ± 0.452698	408.563 ± 0.442229	408.371 ± 0.445739
$T3$	613.109 ± 0.554558	612.956 ± 0.545412	612.775 ± 0.540818

3.3.4 Results

From these evaluation results, we interpret the constant values obtained as that during each period of time T the hub allocates a fixed number of time intervals for itself and for the nodes. Accordingly, the values of the energy consumed and the throughput remain constant, even with the increase in the network density. Hence,

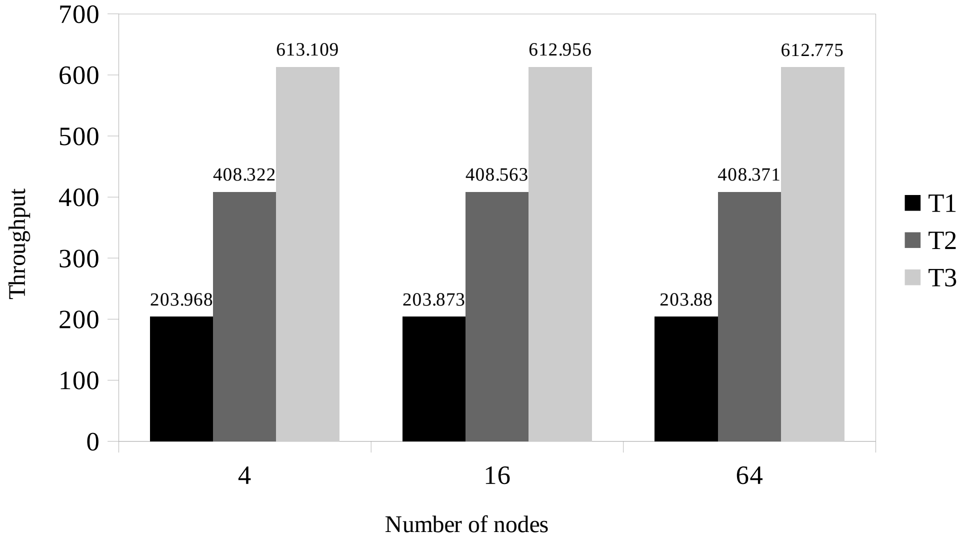


FIGURE 3.10: Averages of the maximum numbers of successful transmitted frames within three networks and during three periods of time.

by extending the period of time T, we can get more time intervals, as well as more throughput rate and more energy consumption. As we interpret the double number of the allocated time intervals of the hub compared to the nodes as that the posting access method, as modeled in Section 3.2, provides the priority to the hub to allocate more time intervals to still communicating with the nodes despite the growth of the network density. This is due to its important role in the network as a controller and a monitor device.

As a result, with the posting access method, the hub works with the same performance, even with the increase in the network density. Thus, validating the scalability of the posting access method, and therefore, validating the scalability of the WBAN.

3.4 Conclusion

In this chapter, we used the statistical model checking toolset UPPAAL-SMC to investigate the posting access method under the WBANs stochastic environment. Based on UPPAAL-SMC, we modeled and evaluated the behavior of the posting access method in terms of scalability. We first used the stochastic timed automata formalism to construct a model of this behavior. Then we used the metric interval temporal logic specifications to evaluate it. The evaluation results showed that, with the posting access method, the hub works with the same performance in terms of the allocated time intervals, the energy consumed, and the throughput, even with the increase of the network density. The thing that validated the scalability of the posting access method and, therefore, the scalability of the WBAN.

Chapter 4

CSMA/CA Access Method: Performance Evaluation

The CSMA/CA mechanism is extensively used by many MAC protocols (Akyildiz and Vuran, 2010). For instance, it is a part of the IEEE 802.11 MAC protocol, designed for wireless local area networks (WLANs). It is also used in the IEEE 802.15.4 MAC protocol, dedicated to low data rate, low consumption wireless networks. Along this, it is a part of the IEEE 802.15.6 MAC protocol. The CSMA/CA version of the IEEE 802.15.6 MAC protocol (Association et al., 2012) is a contention-based access method, whereby a node obtains allocations in EAPs, RAPs, or CAP, to initiate one or more frame transactions for the unpredictable data traffic. Due to the sensitivity of the medical data, evaluating and improving the performance of the IEEE 802.15.6 CSMA/CA access method is crucial. Especially, since the CSMA/CA access method generally suffers from the loss of its performance with the increase of the network density (Akyildiz and Vuran, 2010): the energy consumption increases during the transmissions and the idle listening periods. As well, the collision avoidance mechanism becomes inactive due to the backoff counter (BC) selection procedure, or the increase in the number of hidden nodes. These limitations are the reason for many evaluations and version modifications of CSMA/CA. In this chapter, we evaluate the performance of the IEEE 802.15.6 CSMA/CA access method with regards to WBAN requirements. In order to do this, we estimate the energy-efficiency, throughput, and delay according to the maximal average of: (1) the number of collisions, (2) the value of waiting time in idle listening sources, and (3) the number of packets successfully transmitted. To perform the evaluation, we use the statistical model-checking toolset UPPAAL-SMC, as defined in Subsection 2.4.3:

1. The stochastic timed automata (STA) formalism provided by UPPAAL-SMC allows to build a model for the CSMA/CA access method.
2. The metric interval temporal logic (MITL) specifications are used to evaluate the behavior of the CSMA/CA access method, according to a guiding case study.

The rest of the chapter is organized as follows: the next Section 4.1 provides a detailed description of the CSMA/CA access method. Section 4.2 presents the behavior modeling of the CSMA/CA access method through the STA formalism. In Section 4.3, we propose a case study for the performance evaluations. Section 4.4 provides the experimental evaluation of the CSMA/CA access method through

TABLE 4.1: Relationship between the UPs of medical data traffic and the CWs bounds for the IEEE 802.15.6 CSMA/CA access method (Association et al., 2012).

UP	$CWmin$	$CWmax$	Data traffic designation
5	4	8	For normal medical data
6	2	8	For high priority medical data
7	1	4	For emergency or medical implant event report

the MITL specifications. Section 5.4 concludes the chapter. The CSMA/CA access method will refer, in the rest of this chapter, to the CSMA/CA flavor of the IEEE 802.15.6 MAC protocol.

4.1 CSMA/CA access method: behavior description

When the node wants to obtain a new contended allocation to transmit a new frame or to re-transmit an old frame of a user priority (UP), it should initialize its back-off counter (BC) to zero and then proceed the CSMA/CA access method. Based on the CSMA/CA access method, to obtain a contended allocation in EAP1, RAP1, EAP2, RAP2, or CAP of beacon mode with superframes, the node should first receive the Beacon that specifies the start and end times of these access phases, as defined in Section 2.3. The node obtains a contended allocation in EAP1 and EAP2, only if it needs to send data frames of the highest user priority. It can also treat the combined EAP1 and RAP1 as a single EAP1 and the combined EAP2 and RAP2 as a single EAP2, to send data frames of the highest user priority. The node obtains a contended allocation in RAP1, RAP2, and CAP, to send data frames of different user priorities. For the CSMA/CA access method, there is a relationship between the user priority of the data traffic and the contention window (CW) bounds $CWmin$ and $CWmax$. We mention that in this work, we just use the user priorities of medical data traffic, as depicted in Table 4.1.

4.1.1 Initializing the contention

To employ CSMA/CA access method, as illustrated in Figure 4.1, the node should maintain the CW and the BC to determine when it will obtain a new contended allocation. It sets its BC to an integer sampled randomly from a uniform distribution over the interval $[1, CW]$, where CW is chosen as follows:

1. If it is the first time that the node wants to obtain a contended allocation to transmit one or more frames, it sets its CW to $CWmin[UP]$.
2. If the node wants to obtain a new contended allocation to transmit or re-transmit one or more frames after the last success of its frame transmission, in the last contended allocation it had obtained, it sets its CW to $CWmin[UP]$.
3. If the node transmitted a frame requiring no acknowledgement, late acknowledgement, or group of acknowledgements at the end of its last contended allocation, it should keep the CW unchanged.

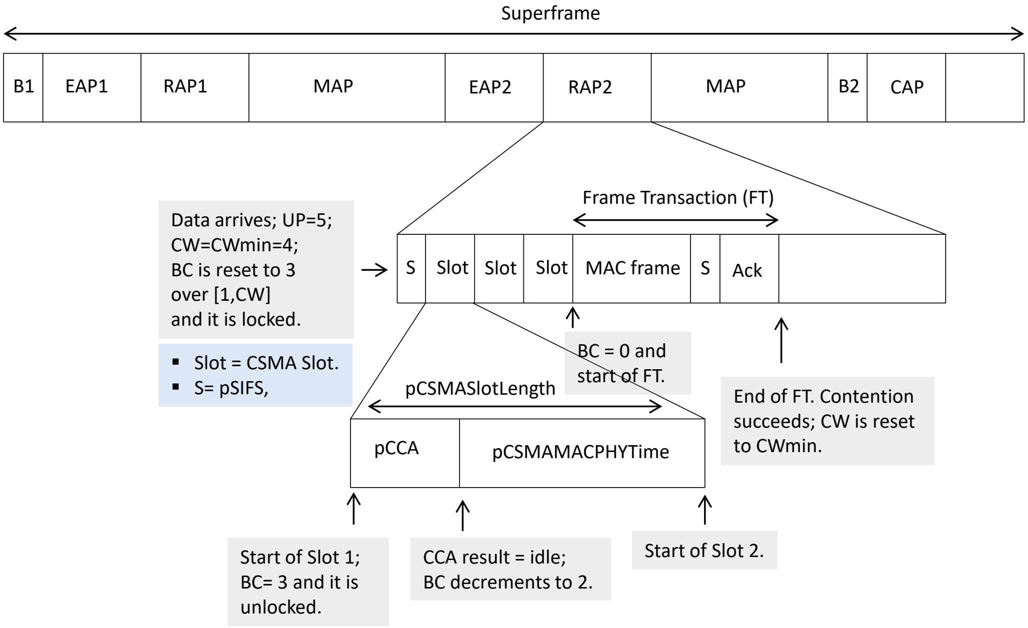


FIGURE 4.1: IEEE 802.15.6 CSMA/CA access method illustration that is based on the illustration in (Association et al., 2012).

4. If the node failed its frame transmission and wants to obtain a new contended allocation to re-transmit it:
   (a) It should not change its CW if it had failed consecutively for an odd number of re-transmissions (i.e., the first transmission is included).
   (b) It should double its CW if it had failed consecutively for an even number of re-transmissions (i.e., the first transmission is included):
      i. If the double of CW exceeds the $CWmax[UP]$, the node should set its CW to $CWmax[UP]$.
      ii. Else the node sets its CW to double of CW.

4.1.2 Starting the contention

After maintaining the CW and the BC, the node locks the BC and waits for a short inter-frame spacing ($pSIFS$) time listening to the channel, then:

1. If the channel is busy during this period of time, the node should wait for the channel freedom.

2. If the channel is still idle during this period of time, the node should compute (T_D) the difference time between the current time (T_C) plus the CSMA Slot duration (T_S) and the end of the current access phase duration (T_{AP}):

$$T_D = T_{AP} - (T_C + T_S) \tag{4.1}$$

(a) If there is enough time to complete a frame transaction ($T_D >= T_f$, where T_f is the time required to complete a frame transaction), the node unlocks its *BC* and waits for the start of the following CSMA Slot.

(b) Else ($T_D < T_f$) the node waits for the next access phase. Then, it restarts the contention.

When the CSMA Slot starts, the node should compute $T_{D'}$ the difference time between the end of the current CSMA Slot and the end of the current access phase:

$$T_{D'} = T_{AP} - (T_{C'} + T_S) \tag{4.2}$$

Where $T_{C'}$ is the current time value because the node waited for the current CSMA Slot's start.

1. If there is enough time to complete a frame transaction ($T_{D'} >= T_f$), the node waits for a clear channel assessment (*pCCA*) time listening to the channel.

2. Else ($T_{D'} < T_f$) the node should lock its *BC* and wait for the next access phase. Then, it restarts the contention steps.

If the channel is still idle during *pCCA* time, the node should decrement its *BC* by one:

1. If the *BC* reaches zero, the node should obtain its contended allocation, which starts at the end of the current CSMA Slot.

2. Else the node waits for the start of the next CSMA Slot and repeats the same steps until the *BC* reaches zero.

If the channel is still busy during *pCCA* time, the node should lock its *BC* and wait for the channel freedom. Then, it repeats the same steps when the CSMA Slot starts.

4.1.3 Using and ending the contended allocation

When the node obtains its contended allocation, it gets ready to start the transmission or the re-transmission of its frame at the end of the current CSMA Slot.

After sending to the hub a frame, the node should receive an expected acknowledgment frame if it requires it, then:

1. If it has no new frame to transmit or no old frame to re-transmit, it should end its contended allocation.

2. Else, it should wait for a *pSIFS* time before sending the frame with (a) an *UP* not lower than the *UP* used to obtain the current contended allocation, (b) the time duration between the current time plus *pSIFS* time and the end of the current access phase is enough for completing the frame transaction, and (c) the number of frames transmitted in this contended allocation should not be more than *mCSMATxLimit*.

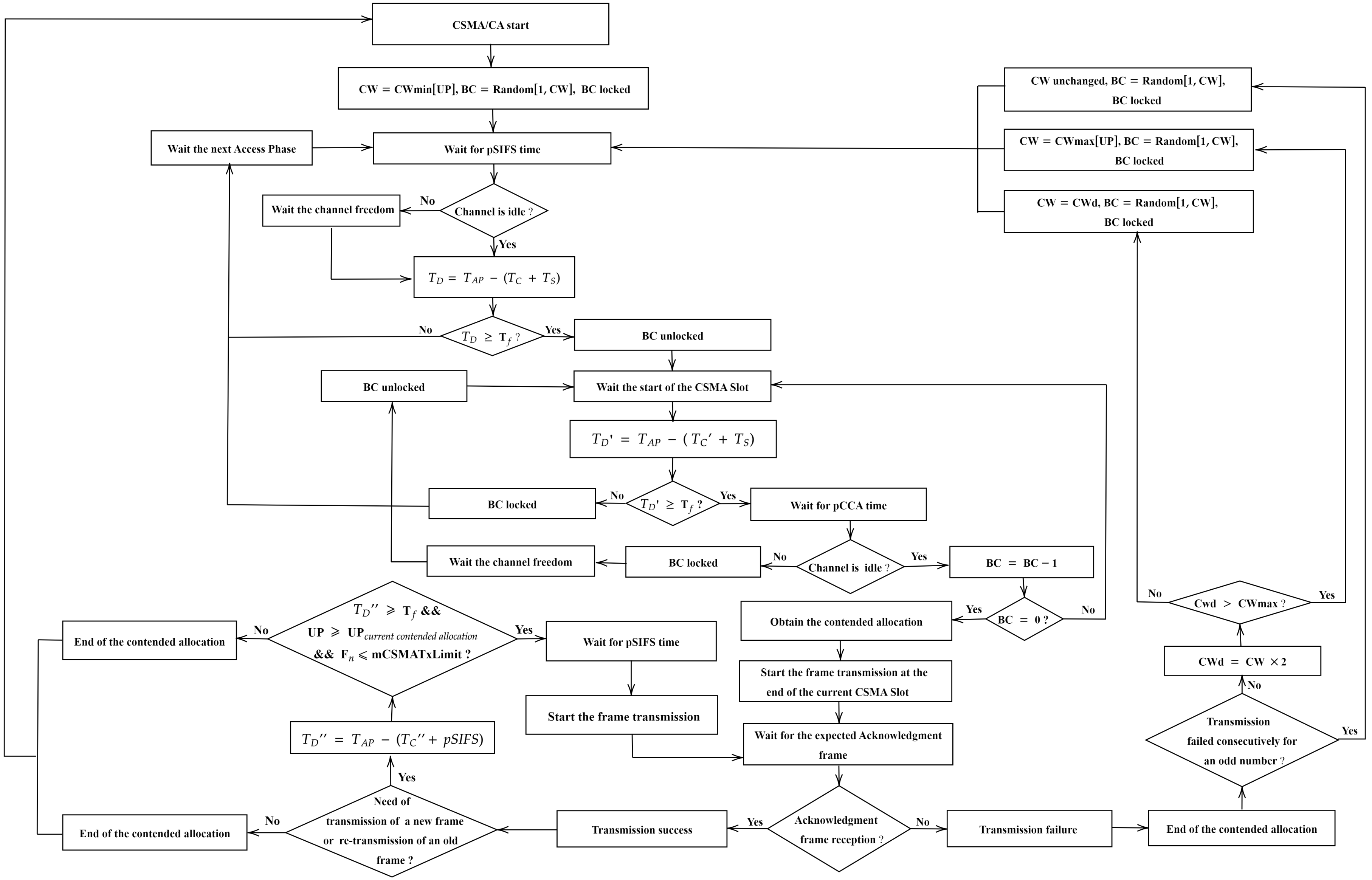


FIGURE 4.2: IEEE 802.15.6 CSMA/CA access method detailed algorithm.

In the case of failing to receive the expected acknowledgment frame, the node should end its contended allocation and repeat the CSMA/CA access method steps to obtain a new contended allocation to re-transmit its frame.

In the next section, we proceed with the CSMA/CA access method behavior modeling through the UPPAAL-SMC modeling formalism.

4.2 CSMA/CA access method: behavior modeling

In the following, we describe the network of stochastic timed automata (NSTA) used to model the behavior of the CSMA/CA access method. We propose five templates, which are the Access Phase, the Slot Timer, the Channel, the Hub, and the Node templates.

4.2.1 Access Phase template

The Access Phase template, as shown in Figure 4.3, is used to indicate the start of the access phase (AP). The location *FirstPeriod* combines the first AP (RAP1) in the superframe structure and its next NAP (MAP and EAP2). The location *SecondPeriod* combines the second AP (RAP2) in the superframe structure and its next NAP (MAP and B2). The location *LastPeriod* combines the third AP (CAP) in the superframe structure and its next NAP (the useless part of the superframe, B1, and EAP1). The $AP1$, $AP2$, or $AP3$ are the durations of the first, second, and third periods, respectively. When the global clock t reaches $AP4$, $AP3$, or $AP2$, the Access Phase automaton sends to the Node automaton the synchronization signal $AP!$ indicating the start of the next access phase. Then, the Access Phase automaton resets its global clock t ($t = 0$) and moves to its next location.

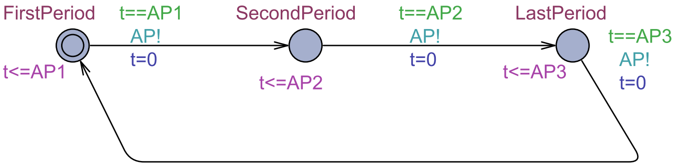


FIGURE 4.3: Access Phase template.

4.2.2 Slot Timer template

The Slot Timer template, as shown in Figure 4.4, is used to indicate the start of CSMA Slot. When the global clock s reaches $pCSMASlotLength$ ($s == pCSMASlotLength$), the Slot Timer automaton sends the synchronization signal $ST!$ to the Node automaton indicating the start of the CSMA Slot. Then, it resets its global clock s ($s = 0$) and moves to the location *SlotTimer*.

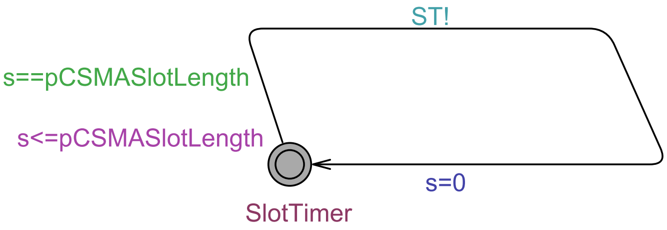


FIGURE 4.4: Slot Timer template.

4.2.3 Channel template

The Channel template, as shown in Figure 4.5, is used to specify the channel state (i.e., idle or busy). When the Channel automaton receives from the Node automaton the synchronization signal *Start*? indicating the start of the frame transmission, it updates the Boolean variable ($ChannelFree = false$), which means that the channel is becoming busy, then it moves to the location *Busy*. When the Channel automaton receives from the Hub automaton the synchronization signal *End*? indicating the end of the contended allocation of the Node, it updates the Boolean variable ($ChannelFree = true$), which means that the channel becomes free, then it moves to the location *Idle*.

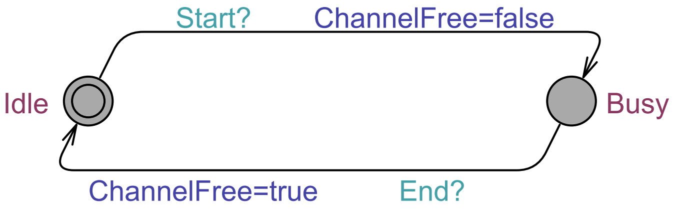


FIGURE 4.5: Channel template.

4.2.4 Hub template

The Hub template, as shown in Figure 4.6, is used to model the behavior of the hub. After receiving from the Node automaton the signals *Start*? and *Sent*? indicating respectively the start and the end of the frame transmission, the Hub waits for $pSIFS$ time ($h == pSIFS$, h is the local clock of the Hub) in the location *HpSIFS*. After that, it sends to the Node the signals *Ack*! and *EAck*! indicating respectively the start and the end of the acknowledgement frame transmission, if the counter n is equal to one ($n == 1$, it means that the Hub received one frame). Then, it sends the broadcast signal *End*! to the Node and the Channel indicating the end of the contended allocation of the Node. When the Hub receives at overlapping times more than one signal *Start*? ($n > 1$, it represents the collision case), it waits for the reception of all signals *Sent*? (when the counter c reaches zero $c == 0$), then it sends the broadcast signal *End*! to the Node automaton and to the Channel automaton to indicate the end of the contended allocation. The counters *Coll* and *Succ* are used to compute the number of collisions and the number of successful receptions of frames, respectively.

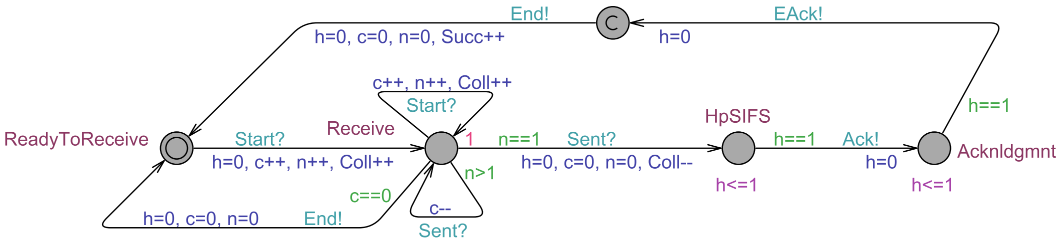


FIGURE 4.6: Hub template.

4.2.5 Node template

The Node template, as shown in Figure 4.7, represents all the steps of the IEEE 802.15.6 CSMA/CA access method used by the node that has one data frame to transmit in its contended allocation.

When the node has data to transmit, it starts the contention to gain a contended allocation. The node can sense data before the APs. In this case, it should enter the contention at the start of the next AP. Otherwise, the node can sense data and enter the contention at an unpredictable time during the APs. The start of the Node automaton models the stochastic interpretation of the non-deterministic time of data sensed by the node during an AP.

To model the non-deterministic data traffic type sensed by the node, we proceed according to the following steps:

$$e0 : randup,\ UP[id] = e0 \tag{4.3}$$

Where, $randup \in [1, 3]$ and id is the identifier of the node.

After the selection of UP and therefor CW, the Node automaton can determine its BC, which is selected as follows:

$$ei : randi,\ BC[id] = ei \tag{4.4}$$

Where, $randi \in [1, CW\_min(i)]$ and $i \in [1, 3]$

We model the time required to complete the frame transmission as ($Tf[id] = Tp$). Where the Tp is the total duration of the packet that should transmit.

After waiting for a $pSIFS$ time ($y == pSIFS$, y is the local clock of the Node) in the location *WaitpSIFS* or after waiting the $pCCA$ time in the location *WaitpCCATime*, the Node tests the channel freedom by the *Boolean* guard $ChannelFree$:

1. The guard ($ChannelFree == false$) means that the channel is busy. In this case, the Node should move to the location *WaitChanlFreedom1* or to the location *WaitChanlFreedom2* until the reception of the signal *End*?.

2. The guard ($ChannelFree == true$) means that the channel is idle. In this case, the Node should know whether there is enough time to complete its frame transaction or not:

(a) If this guard ($t <= APd - (pCSMASlotLength + Tf[id] + (pSIFS + mACK + mTimeOut)))$ is valid, the Node moves to the location *WaitStartCSMASlot1* waiting for the start of CSMA Slot or to the location *WaitpCCATime* waiting for a $pCCA$ time.

(b) Else the Node moves to the location *WaitNxtAccPhase* waiting for the next access phase.

Once the guard ($s == pCCATime$ && $ChannelFree == true$) is verified, the Node decrements its BC by one ($BC[id] - -$). When the BC reaches zero ($BC[id] == 0$), the Node moves to the location *WaitStartCSMASlot2* waiting for the signal ST? to start the transmission of its frame. This transmission starts and ends by sending two broadcast signals $Start$! and $Sent$! respectively. After receiving from the Hub the *Acknowledgement* frame, the Node moves to the location *TransSuccess*. When the Node fails the frame transmission, it should maintain another BC according to the cases that are defined in Subsection 4.1.1. To maintain a new BC, the Node should compute the number of its successive failures. We use the counter $Failure[id]$ to compute this number:

1. For $UP[id] == 1$ or $UP[id] == 2$, if:
    (a) $Failure[id] == 1$, $BC[id] \in [1, CW\_min(i)]$
    (b) $Failure[id] == 2$, $BC[id] \in [1, CW\_min(i)db]$
    (c) $Failure[id] == 3$, $BC[id] \in [1, CW\_min(i)db]$
    (d) $Failure[id] >= 4$, $BC[id] \in [1, CW\_max(i)]$
2. For $UP[id] == 3$
    (a) $Failure[id] == 1$, $BC[id] \in [1, CW\_min(i)]$
    (b) $Failure[id] >= 2$, $BC[id] \in [1, CW\_max(i)]$

Where, $CW\_min(i)db$ is the double of $CW\_min(i)$.

Then, the Node moves to the location *WaitNxtAccPhase* waiting for the next access phase if there is not enough time in the current access phase. Otherwise, it moves to the location *WaitpSIFS* to repeat the process until getting the contented allocation.

4.3 Performance evaluation case study

To evaluate the performance of the CSMA/CA access method, based on NSTA model and according to WBAN requirements, we propose in this section a WBAN case study.

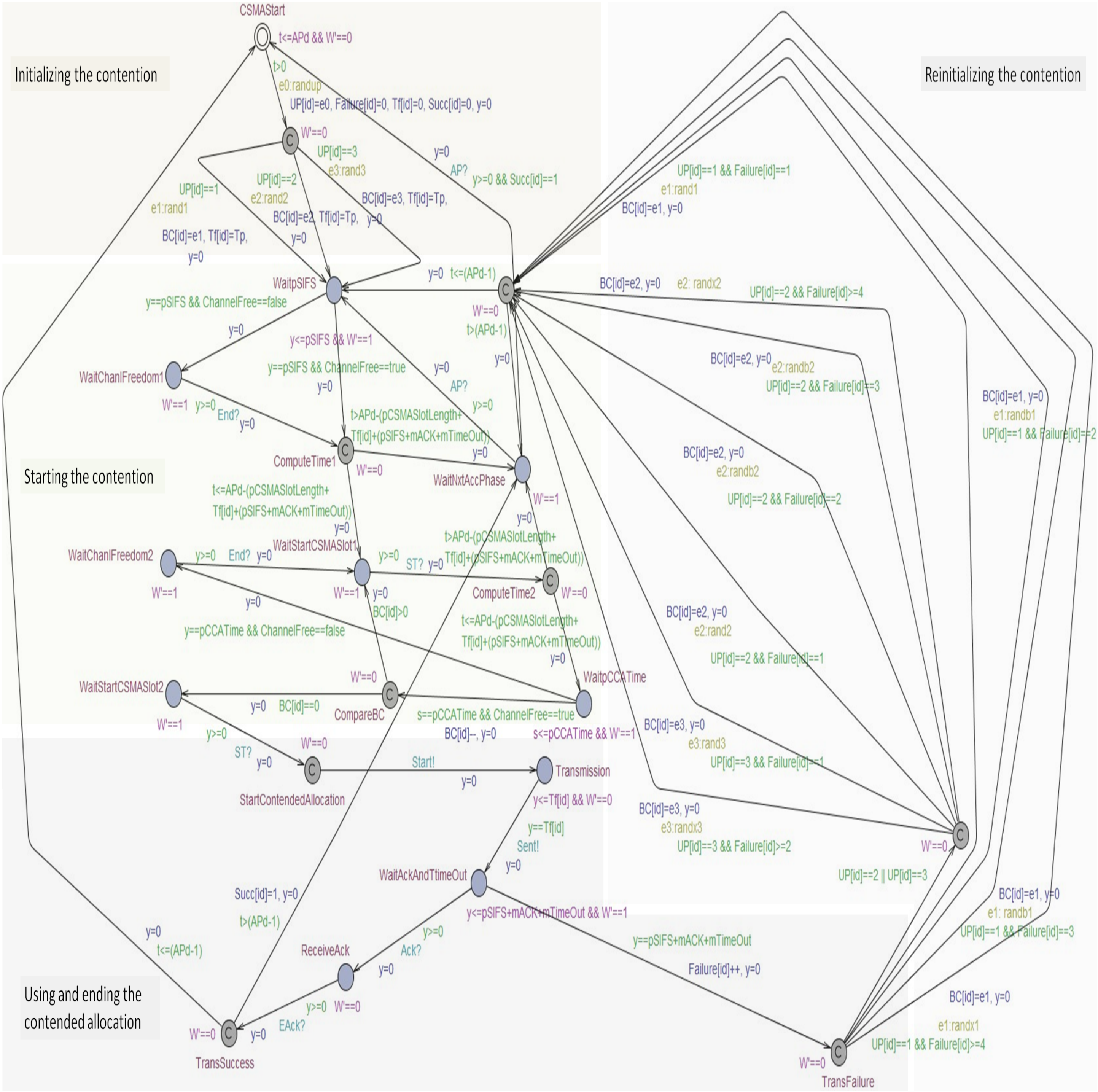


FIGURE 4.7: Node template: it represents all the steps of the IEEE 802.15.6 CSMA/CA access method, as described in Section 4.1 and represented in Figure 4.2, used by a node that has one data frame to transmit in its contended allocation.

4.3.1 Case study considerations and assumptions

We consider a WBAN of one hub and a number of nodes ranging from 8 to 64. In order to evaluate the scalability of the WBAN, we consider 4 networks with a different number of nodes. The first network consists of a hub and 8 nodes, 16 nodes for the second one, 32 nodes for the third one, and 64 nodes for the fourth one. The star network topology is used, where the hub and all the nodes communicate directly.

The simulation results in (Rashwand and MišIć, 2012; Rashwand, Mišić, and Mišić, 2015) showed that the presence of EAPs is not necessary for a typical WBAN, while the results in (Rashwand, Mišić, and Mišić, 2015) revealed that four user priorities ($UP4$, $UP5$, $UP6$, and $UP7$) typically suffice to achieve even the most stringent requirements for WBAN performance, and the user priorities ($UP0$, $UP1$, $UP2$, $UP3$, $UP4$, and $UP5$) provide the same results. By virtue of these simulation results, we use in this case study the access phases RAP1, RAP2, and CAP, and the user priorities $UP5$, $UP6$, and $UP7$.

We consider a heterogeneous network where the node has different user priorities of medical data traffic types ($UP5$, $UP6$, and $UP7$). The values of the $CWmin$ and $CWmax$ in (Association et al., 2012) are used. We assume that every node transmits one data frame in its contended allocation. The time when the node starts the contention and the data type are non-deterministic. We consider a saturation condition, whereby all nodes of the network have one data frame to transmit at all non-deterministic time. The channel is ideal and the failed transmissions are due to collisions only. Each network is assigned a different superframe scenario with a different number of access phases (APs) and non-access phases ($NAPs$). The first scenario (*Scenario1*) has one AP, the second one (*Scenario2*) has two APs and one NAP in between, and the third scenario (*Scenario3*) has three APs and two $NAPs$ in between, as depicted in Figure 4.8 and Table 4.2.

The values of the other parameters used in this case study are presented in Table 4.3.

4.3.2 IEEE 802.15.6 packet structure and transmission duration

The packet as defined in IEEE 802.15.6 (Association et al., 2012) is composed of the physical layer service data unit (PSDU), the physical layer convergence protocol (PLCP) preamble, and the PLCP header. Based on the following IEEE 802.15.6 equations, which are detailed in (Association et al., 2012), we compute the total time duration of the data and the acknowledgment packets:

$$t_{packet} = T_s \times [N_{preamble} + N_{header} \times S_{header} + \frac{N_{total}}{log_2(M)} \times S_{PSDU}] \tag{4.5}$$

$$N_{total} = N_{PSDU} + N_{CW} \times (n-k) + N_{pad} \tag{4.6}$$

$$N_{pad} = log_2(M) \times [\frac{N_{PSDU} + N_{CW} \times (n-k)}{log_2(M)}] - [N_{PSDU} + N_{CW} \times (n-k)] \tag{4.7}$$

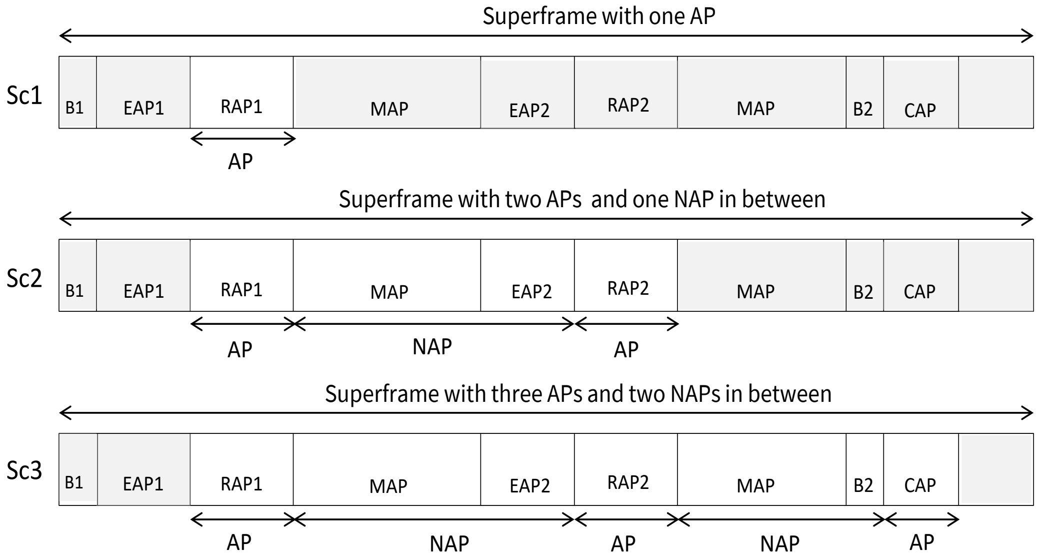


FIGURE 4.8: Superframe scenarios. Sc1: *Scenario1*. Sc2: *Scenario2*. Sc3: *Scenario3*.

$$N_{CW} = [\frac{N_{PSDU}}{k}] \tag{4.8}$$

$$N_{PSDU} = (N_{MACheader} + N_{MACFrameBody} + N_{FCS}) \times 8 \tag{4.9}$$

Due to the small size of the medical information that should be transmitted to the hub, we assume using a frame with a fixed length.

Based on the 402 MHz to 405 MHz frequency narrowband of the physical layer for medical applications, we consider the data rate parameter values, as depicted in Table 4.3, to compute data and acknowledgment packets time durations used in this case study.

4.3.3 WBANs evaluation metrics

We consider the evaluation of specific WBAN applicative metrics related to the energy-efficiency, throughput, and delay requirements.

Energy-efficiency

The energy-efficiency, as defined in (Akyildiz and Vuran, 2010), means that the node should work with minimum energy consumption. The energy consumption is the dominant problem of MAC protocols design in wireless sensor networks. Its sources are communication, followed by processing, and sensing, in decreasing consumption order. The energy consumption during the communication task is due to transmission and reception power choice, collisions, and idle listening. The first two are the major sources of energy consumption. Collisions become the major source of energy consumption when their number increases in the network and, the idle listening becomes the major source of energy consumption when the nodes spend a long idle time listening to the channel.

The increase or the decrease of the energy consumption amount depends on the number of collisions and the time spent in the idle listening locations.

To know how the CSMA/CA access method exploits the energy-efficiency during the communication task, we propose to evaluate its behavior in terms of collisions and waiting time in idle listening locations.

Throughput

The throughput is considered as a key to determine the performance of a network (Kiesel and Kuehn, 1983). The throughput of a node (in bits/second) is defined, in (Sarkar et al., 2015; Kumar and Gupta, 2016; Hiep, Kohno, et al., 2017), as the number of bits or packets successfully transmitted over the channel in time units:

$$Throughput = \frac{Number\ of\ bits\ successfully\ transmitted}{Unit\ time} \tag{4.10}$$

The throughput is defined for a network, in (Hiep, Hoang, and Kohno, 2015), as the average amount of information transmitted in each slot. Due to the small size of the IEEE 802.15.6 slot, we define the throughput as the average of the number of packets successfully transmitted over the superframe.

Similarly to the energy-efficiency, the increase or decrease of the throughput rate depends on the successful packets transmissions. Based on this, we propose to evaluate the behavior of the CSMA/CA access method in terms of the average number of packets successfully transmitted over the superframe.

Delay

The delay is defined in (Ullah, Chen, and Kwak, 2012) as follows:

$$Delay = T_{CW} + T_{Frame} + T_{I-Ack} + 2T_{pSIFS} + T_{TimeOut} \tag{4.11}$$

The value of the time required for the frame transmission (T_{Frame}), the acknowledgment frame (T_{I-Ack}), *pSIFS* time ($2T_{pSIFS}$), and the time out *TimeOut* ($T_{TimeOut}$) are considered fixed. However, the time required for the contention window (T_{CW}) is considered variable. Therefore, it is the metric that defines the increase or the decrease in the delay. For this reason, we propose to evaluate the delay according to the value of the time spent during the contention window through the calculation of the waiting time during the contention.

Based on all the considerations and the definitions presented in this section, we propose to evaluate:

- The energy-efficiency according to the average maximal number of collisions, and the maximum value of waiting time spent by the nodes in the idle listening sources.
- The throughput according to the average maximal number of packets that are successfully transmitted over the superframe scenario.
- The delay according to the average maximal value of waiting time during the contention window.

TABLE 4.2: Relationship between the superframe scenarios and the number of CSMA Slot.

Superframe scenarios	number of CSMA Slot
scenario1	39
scenario2	123
scenario3	207

TABLE 4.3: Parameters values defined in the IEEE Standard 802.15.6 (Association et al., 2012) and used in our case study.

Data rate(kbps)	151.8
Code rate (k/n)	51/63
$Symbolrate = 1/T_s$ (ksps)	187.5
Superframe	252 CSMA Slots
$pCSMASlotLength$	376 μs
$pMACPHYTime$	40 μs
$mCSMATxLimit$	1
$pCCATime$	336 μs
$mTimeOut$	30 μs
$pSIFS$	75 μs
$mACK$	1336 μs
$N_{preamble}$	90 bits
N_{header}	31 bits
$N_{MACheader}$	7 bytes
$N_{MACBody}$	8 bytes
N_{FCS}	2 bytes
S_{header}	2
S_{PSDU}	1
M	2

4.4 CSMA/CA access method: behavior evaluation

Based on the case study defined in Section 4.3 and the NSTA model described in Section 4.2, we evaluate in this section the performance of the CSMA/CA access method, using UPPAAL-SMC, according to the average of the maximum number of collisions, the maximum value of waiting time spent by the nodes in idle listening sources, and the maximum number of packets successfully transmitted.

To specify properties over the NSTA, we use in this section the evaluation of the expected values of the max property. Its syntax, as adopted by UPPAAL-SMC, is as follows:

- The evaluation of the expected values of *max*:

$$E[bound; N](max : expr) \tag{4.12}$$

  Where $bound$ is a time bound in the evaluation, N is the number of runs, and $expr$ is the expression to evaluate.

4.4.1 Average of maximum collisions

Collisions are occurring when two or more nodes transmit a packet to the same receiver at overlapping times (Akyildiz and Vuran, 2010). Based on this definition, we evaluate the average of the maximum number of collisions.

Evaluation

The Equation 4.13 provides the desired quantity.

$$E[<= T; N](max : Hub.Coll) \tag{4.13}$$

This formula computes the average of the expected maximum value of the counter $Coll$. UPPAAL-SMC estimates this average to be in a confidence interval, as mentioned in Tables 4.4, 4.5, and 4.6.

In our NSTA model, the Hub template uses a counter $Coll$ to compute the number of collisions. The Hub automaton increments the counter ($Coll++$) when it receives the signal of starting the reception of a frame ($Start?$). During the reception time of this frame:

1. If the Hub has received any other signal $Start?$ from one or more nodes, it should increment its counter ($Coll++$), which means that the transmission of the first frame and the frames that followed has failed (i.e., collision).
2. Else, the Hub should decrement its counter ($Coll--$), which means that the frame transmission has not failed.

Results

The evaluation results are depicted in Tables 4.4, 4.5, and 4.6, and also in Figure 4.9. The Tables 4.4, 4.5, and 4.6, show the confidence intervals of the estimated averages of the maximum number of collisions for the four networks and during the three superframe scenarios, respectively. The Figure 4.9 represents the comparison results between these scenarios.

TABLE 4.4: Confidence intervals of the estimated averages of the maximum numbers of collisions.

Superframe's scenario	8 Nodes	16 Nodes	32 Nodes	64 Nodes
Scenario1	2.026 ± 0.665	3.965 ± 0.1060	7.662 ± 0.1476	14.515 ± 0.1969

TABLE 4.5: Confidence intervals of the estimated averages of the maximum numbers of collisions.

Superframe's scenario	8 Nodes	16 Nodes	32 Nodes	64 Nodes
Scenario2	8.489 ± 0.1262	17.429 ± 0.1500	34.921 ± 0.2017	69.161 ± 0.2859

TABLE 4.6: Confidence intervals of the estimated averages of the maximum numbers of collisions.

Superframe's scenario	8 Nodes	16 Nodes	32 Nodes	64 Nodes
Scenario3	15.257 ± 0.1380	31.092 ± 0.1587	62.676 ± 0.2166	124.483 ± 0.2962

The evaluation results of these three scenarios show that: (1) dividing the superframe into short and fixed lengths of the APs, and (2) using the collision avoidance mechanism that aims to select the BC according to the converged CW intervals of the UPs, increase the number of collisions in the network. This is especially true, when the network has a medium and high number of nodes. This number of collisions doubles when we use two or three APs.

4.4.2 Average of maximum waiting time

From our NSTA model of the CSMA/CA access method, we find that the Node template, as depicted in Figure 4.7, has many sources of waiting time, which are with bounded and unbounded time. They are mentioned in their locations by the names that start with *Wait*: *WaitpSIFS*, *WaitChanlFreedom1*, *WaitChanlFreedom2*, *WaitStartCSMASlot1*, *WaitStartCSMASlot2*, *WaitpCCATime*, *WaitAckAndTtimeOut*, and *WaitNxtAccPhase*.

Evaluation

Using the Equation 4.14, we evaluate the average of the maximum value of waiting time spent by the nodes in idle listening sources:

$$E[<= T; N](max : sum(i : id\_t)Node(i).W) \tag{4.14}$$

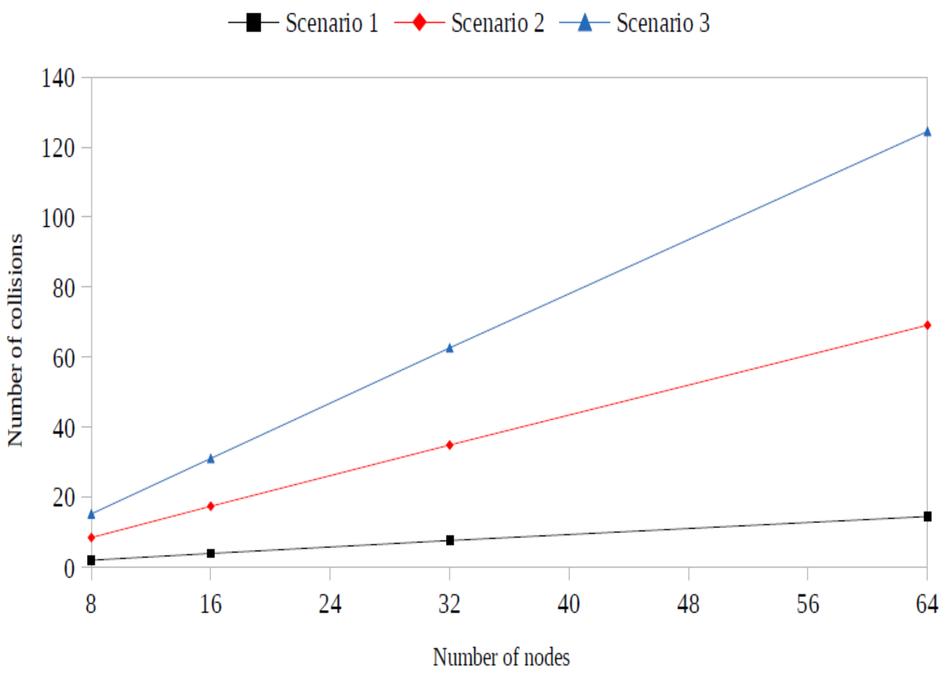


FIGURE 4.9: Collisions comparison results between the three scenarios.

where,

$$W = T_{WaitpSIFS} + T_{WaitChanlFreedom1} + T_{WaitChanlFreedom2} + \\ T_{WaitStartCSMASlot1} + T_{WaitpCCATime} + T_{WaitStartCSMASlot2} + \\ T_{WaitAckAndTtimeOut} + T_{WaitNxtAccPhase} \tag{4.15}$$

This formula computes the average of the maximum value of the clock W for the sum of the nodes of the network. UPPAAL-SMC estimates this average to be in a confidence interval, as mentioned in Tables 4.7, 4.8, and 4.9.

In our NSTA model, the Node template uses a local clock W to compute the time spent by the node in its waiting locations ($T_{Wait(locationname)}$). Setting the clock rate to the value $W == 1$ effectively computes the time spent in a location. Otherwise, setting the clock rate to the value $W == 0$ stops the clock in a location.

Results

The evaluation results are depicted in Tables 4.7, 4.8, and 4.9, and also in Figure 4.10. The Tables 4.7, 4.8, and 4.9 show the confidence intervals of the estimated averages of the the maximum values of the clock W for the four networks and during the three superframe scenarios, respectively. The Figure 4.10 represents the comparison results between these scenarios.

The evaluation results of these three scenarios show that: (1) dividing the superframe into short and fixed lengths of the APs, (2) constructing the CSMA/CA access

TABLE 4.7: Confidence intervals of the estimated averages of the maximum values for the clock W.

Superframe's scenario	8 Nodes	16 Nodes	32 Nodes	64 Nodes
Scenario1	43378.7 ± 621.817	95225 ± 911.137	198790 ± 1304.78	410073 ± 1882.86

TABLE 4.8: Confidence intervals of the estimated averages of the maximum values for the clock W.

Superframe's scenario	8 Nodes	16 Nodes	32 Nodes	64 Nodes
Scenario2	268291 ± 690.066	547065 ± 982.433	1.10596*e* + 006 ± 1393.35	2.22355*e* + 006 ± 1986.56

TABLE 4.9: Confidence intervals of the estimated averages of the maximum values for the clock W.

Superframe's scenario	8 Nodes	16 Nodes	32 Nodes	64 Nodes
Scenario3	493103 ± 793.433	1.00104*e* + 006 ± 1019.29	2.01204*e* + 006 ± 1463.3	4.03425*e* + 006 ± 2098.23

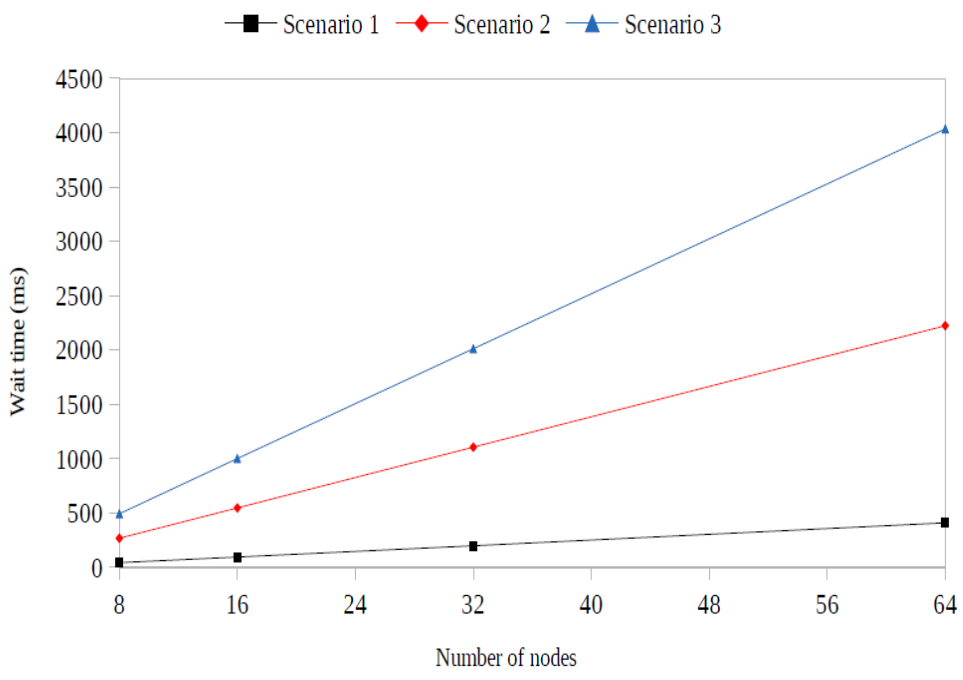


FIGURE 4.10: Comparison results between the three scenarios in terms of the waiting time spent in the idle listening locations.

method with an important number of idle listening sources, and (3) the inactive collision avoidance mechanism that results in a high number of collisions, lead to spend more time in the idle listening locations. This is especially the case for networks with a medium and high number of nodes. The value of W exploded in *Scenario2* and *Scenario3*, where the nodes spend more time in the long periods of the $NAPs$ compared to the *Scenario1* that has not any NAP.

4.4.3 Average of maximum successful transmissions

The IEEE 802.15.6 (Association et al., 2012) defines the successful transmission when the node receives an expected acknowledgment to its last frame transmission. Based on this definition, we evaluate the average of the maximum number of packets successfully transmitted.

Evaluation

Using the Equation 4.16, we evaluate the average of the maximum number of packets successfully transmitted:

$$E[<= T; N](max : Hub.Succ) \tag{4.16}$$

This formula computes the average of the maximum value of the counter $Succ$. UPPAAL-SMC estimates this average to be in a confidence interval, as mentioned in Tables 4.10, 4.11, and 4.12.

In our NSTA model, the Hub template uses a counter $Succ$ to compute the number of packets successfully transmitted. The Hub automaton increments the counter ($Succ++$) after sending the acknowledgment frame to the Node automaton.

Results

The evaluation results are depicted in Tables 4.10, 4.11, and 4.12, and in Figure 4.11. The Tables 4.10, 4.11, and 4.12 show the confidence intervals of the estimated averages of the maximum number of packets successfully transmitted in the four networks and during the three superframe scenarios, respectively. The Figure 4.11 represents the comparison results between these scenarios.

TABLE 4.10: Confidence intervals of the estimated averages of the maximum number of packets successfully transmitted.

Superframe's scenario	8 Nodes	16 Nodes	32 Nodes	64 Nodes
Scenario1	1.227 ± 0.0321	0.938 ± 0.0256	0.72 ± 0.0281	0.569 ± 0.0307

TABLE 4.11: Confidence intervals of the estimated averages of the maximum number of packets successfully transmitted.

Superframe's scenario	8 Nodes	16 Nodes	32 Nodes	64 Nodes
Scenario2	1.587 ± 0.0444	1.004 ± 0.0319	0.71 ± 0.0286	0.552 ± 0.0309

TABLE 4.12: Confidence intervals of the estimated averages of the maximum number of packets successfully transmitted.

superframe's scenario	8 Nodes	16 Nodes	32 Nodes	64 Nodes
Scenario3	1.839 ± 0.0534	1.039 ± 0.0348	0.723 ± 0.0287	0.579 ± 0.030

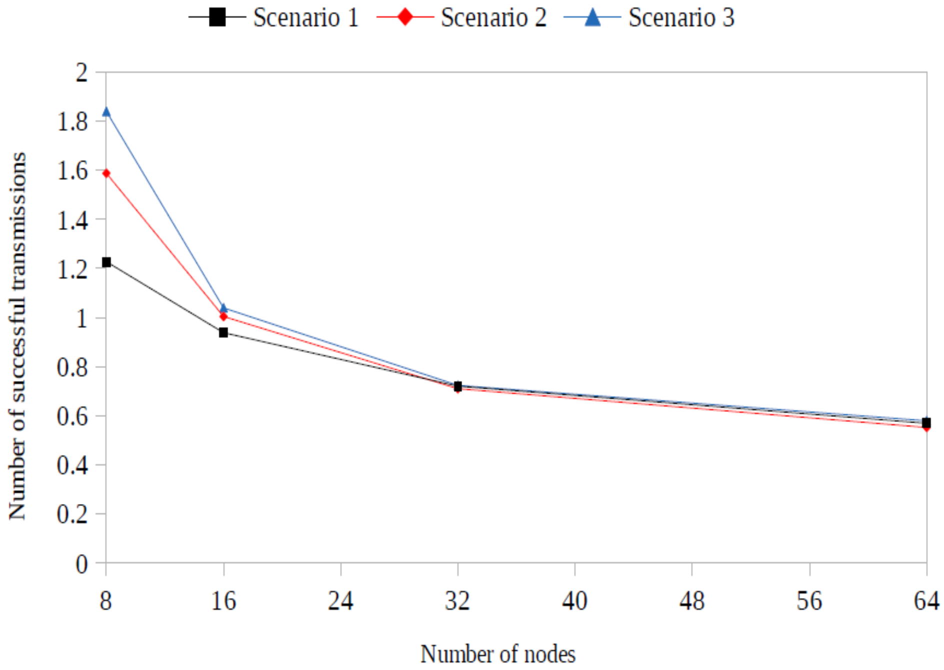


FIGURE 4.11: Successful transmissions comparison results between the three scenarios.

The evaluation results of these three scenarios show that: (1) dividing the superframe into short and fixed lengths of *APs*, (2) using one or three *APs*, (3) choosing the *BC* according to the converged *CW* intervals of the *UPs* that results in the high number of collisions, and (4) constructing the IEEE 802.15.6 CSMA/CA access method with an important number of idle listening sources that allowed the nodes to spend more time there, have a negative impact on the number of successful transmissions.

4.5 Results analysis

In this chapter, we evaluated, based on a case study and using UPPAAL-SMC, the performance of the CSMA/CA access method in terms of the WBAN requirements. We evaluated quantitatively the energy-efficiency, the throughput, and the delay according to the average of the maximum: (1) number of collisions, (2) value of waiting time in idle listening sources, and (3) number of packets successfully transmitted.

Through this evaluation, we found that under the saturation condition, the short and fixed lengths of the access phases (RAP1, RAP2, and CAP) could not cover the medium and high traffic, where an access phase allows just a limited number of nodes to transmit or re-transmit their frames. The converged *CW* intervals of the *UPs* increase the probability of choosing the same *BC*. Thus increases the number of collisions that is accumulated progressively by using other access phases. In addition, the construction of the CSMA/CA access method with many idle listening sources, including the long periods of the non-access phases, leads to spend more time in these locations that is also accumulated progressively by using other access phases. Therefore, the performance of the WBAN impacted negatively in terms of energy-efficiency, throughput, and delay.

Our finding is consistent with other studies that are made in another context, as cited in Subsection 2.3.1, demonstrating that dividing the axis time into superframes with short and fixed lengths of the *APs*, and classifying the data frames according to the user priorities with converged *CW* intervals have not resolved the problem of the CSMA/CA. This is represented through the loss of its performance with the increase of the network density. The simulation results of the study in (Khan et al., 2014) demonstrated that using different access phases degrades the overall system throughput performance. In addition, the results of the study in (Rashwand and MišIć, 2012) proved that the use of short RAPs lead to inefficient use of the bandwidth. This is because the existence of inaccessible slots at the end of the RAPs and the high collisions probability at the beginning of RAPs are the main reasons for the performance deterioration in the case of having shorter RAPs. Moreover, the simulation results of the study in (Rashwand, Mišić, and Mišić, 2015) indicated that using small *CW* sizes for all user priorities lead to early saturation by increasing the collision probability under medium to high network traffic volume. As the simulation results of (Ullah, Chen, and Kwak, 2012) showed that for multiple nodes, a lot of collisions occur and the nodes go to the backoff several times, which degrades the maximum throughput of the network and further affects the delay.

To overcome the IEEE 802.15.6 CSMA/CA access method limits, the authors in (Rashwand and MišIć, 2012) proposed to increase the RAPs length to improve the performance of nodes with user priorities different to *UP*7 (for the emergency medical data) in terms of throughput. They proposed also, in the case of high traffic rate of *UP*7, to increase the length of EAPs, because they considered it as a must in this case, and using for *UP*7 the contention-free mechanism as an option. In our case, we propose firstly one access phase with a variable length according to the traffic load for the CSMA/CA access method. This is a result of the negative impact that it has shown on the structure of the superframe. This structure divided the time axis into access phases with short and fixed lengths and non-access phases with long and fixed lengths. The first access phases allow a low number of transmissions, while the second access phases allow long idle listening periods. Secondly, we propose an optimization of the idle listening sources of the CSMA/CA access method. Thirdly, for the problem of the collision avoidance mechanism, which is represented by the converged intervals of *CW*, we intend to apply a new distribution of the *CW* intervals to decrease the probability of collisions, as well as a *BC* selection procedure under these *CW* proposed intervals.

4.6 Conclusion

In this chapter, we evaluated, using the statistical model-checking (SMC) toolset UPPAAL-SMC, the performance of the IEEE 802.15.6 CSMA/CA access method, with regard to WBAN requirements. Through a case study, we analyzed quantitatively the energy-efficiency, throughput, and delay according to the average of the maximum: (1) number of collisions, (2) waiting time in idle listening sources, and (3) number of packets successfully transmitted.

In a nutshell, for the standard IEEE 802.15.6 CSMA/CA access method, the evaluation results showed that under the saturation condition, the short and fixed lengths of the access phases (RAP1, RAP2, and CAP) could not cover the medium and high traffic. The converged *CW* intervals for the user priorities (UP5, UP6, UP7) increase the number of collisions. In addition, idle listening sources lead to spend more waiting time in these locations. Therefore, the performance of the WBAN is impacted negatively in terms of energy-efficiency, throughput, and delay.

Chapter 5

CSMA/CA Access Method: Performance Enhancement

In this chapter, we describe and evaluate our proposed *CW* intervals and *BC* selection procedure (proposed CSMA/CA will refer to this proposition). Then, we compare the effectiveness of our proposed CSMA/CA with the effectiveness of the standard CSMA/CA (standard CSMA/CA referred to as the IEEE 802.15.6 CSMA/CA) in terms of the average of the maximum number of collisions, the maximum value of waiting time spent by the nodes in idle listening sources, and the maximum number of packets successfully transmitted.

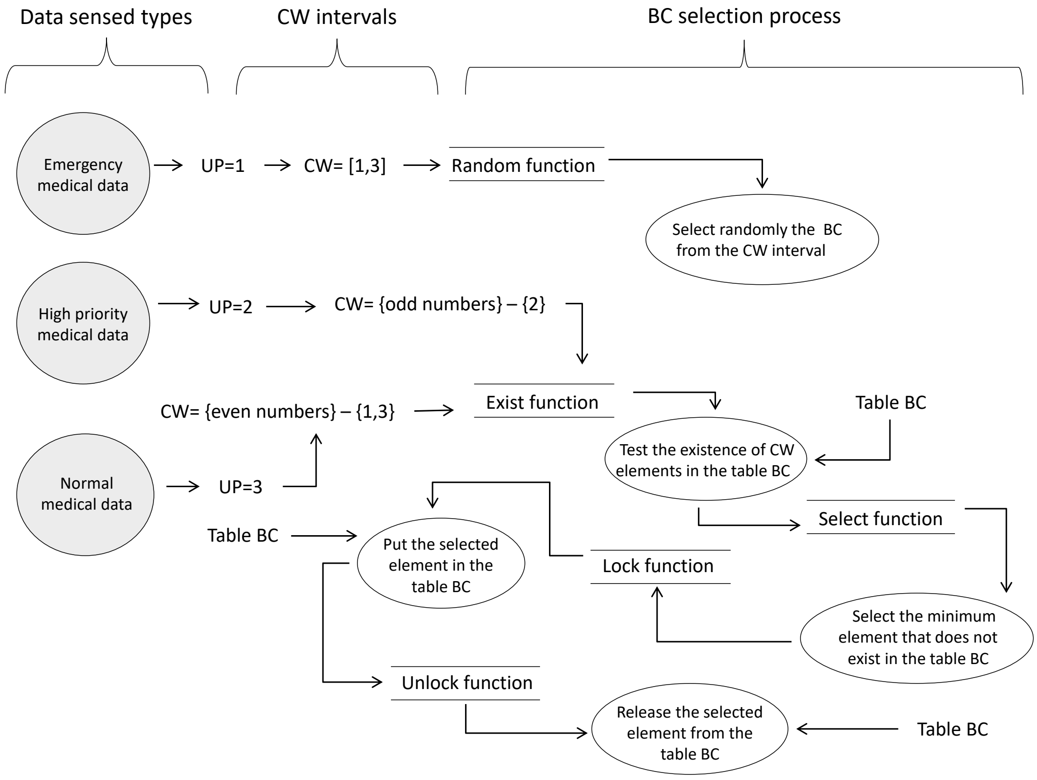


FIGURE 5.1: Our proposed *CW* intervals and *BC* selection procedure: the figure's design is inspired by the article (Lamine et al., 2020).

The rest of the chapter is organized as follows: the next Section 5.1 describes the proposed CSMA/CA. Section 5.2 evaluates the proposed CSMA/CA. Section 5.3 gives a comparison analysis of the the proposed CSMA/CA. Section 5.4 concludes the chapter.

5.1 Description

To select the BC, we propose three CW intervals according to the UPs of the medical data traffic, as well as the methods used for the BC selection, as depicted in Table 5.1, Algorithms 1, 2, 3, 4, and Figure 5.1. We note that we use the same process of the BC selection for each contention, after success or failed transmission.

For the emergency medical data, the selection procedure of the BC is the same as the selection procedure of the basic IEEE 802.15.6 CSMA/CA access method, where the node sets its BC to an integer sampled from a uniform distribution over the interval $[1, CW]$. While, the interval $[1, CW]$ in our proposition is $[1, 3]$.

In the case of high and normal priorities medical data, the selection procedure of the BC goes through the *Exist*, the *Select*, the *Lock*, and the *Unlock* functions, as defined in the Algorithms 1, 2, 3, and 4, respectively. The principle of these functions together is to select the minimum number of the CW interval that is not selected at the moment of initializing the contention by another node.

UP	CW	Data traffic designation
1	$[1, 3]$	Emergency medical data
2	$\{odd\ numbers\} - \{2\}$	High priority medical data
3	$\{even\ numbers\} - \{1, 3\}$	Normal medical data

TABLE 5.1: UPs and their CW intervals used in our proposed CSMA/CA.

The *Exist* function this function searches the existence of a CW element in the table BC. The table CW represents the numbers of a CW interval. The table BC contains the elements of CW that have been selected by the nodes. The selected elements of CW are the selected BCs, which are put in the table BC associated to each node id. The sizes of the tables CW and BC are equal to the network nodes number, thus the node can select a unique CW element.

The *Select* function this function allows the selection of the minimum element of the table CW that does not exist in the table BC.

The *Lock* function this function puts the selected CW element by a node in the table BC.

After selecting and using the CW element (which means the BC), we use the *Unlock* function.

Algorithm 1: The Exist function

```
Input: $cw$ element of the table $CW$, table $BC$ of $CW$ selected elements
Output: boolean result: $true$ or $false$
$i \leftarrow 0$;
$Size \leftarrow$ size of the table $BC$;
while $i < Size$ do
    if $BC[i] == cw$ then
        return $true$;
    else
        $i \leftarrow i + 1$;
    end
end
return $false$
```

Algorithm 2: The Select function

```
Input: table $CW$ of high or normal priority medical data
Output: $CW[j]$ the minimum non-selected value of the table $CW$
$j \leftarrow 0$ , $SizeCW \leftarrow$ size of $CW$;
while $j < SizeCW$ & $existe(CW[j]) == true$ do
    $j \leftarrow j + 1$;
end
if $j < SizeCW$ then
    return $CW[j]$;
else
    return $-1$;
end
```

Algorithm 3: The Lock function

```
Input: $id_i$ of the $node_i$ , $ms$ the minimum selected elements of the table $CW$
$BC[id_i] \leftarrow ms$;
```

The *Unlock* function this function releases the *CW* element from the table *BC* after its use by the node.

Algorithm 4: The Unlock function

```
Input: $id_i$ of the $node_i$
$BC[id_i] \leftarrow 0$;
```

5.2 Evaluation

Based on the case study defined in Section 4.3 and the evaluation approach detailed in Section 4.4, we evaluate in the following: (1) the average of the maximum number of collisions. (2) The average of the maximum value of waiting time spent by the nodes in the idle listening sources. As well as, (3) the average of the maximum number of packets successfully transmitted for the proposed CSMA/CA.

Average of maximum collisions

The evaluation results are depicted in Figure 5.2. This Figure represents the comparison results between the three scenarios in terms of the average of the maximum number of collisions.

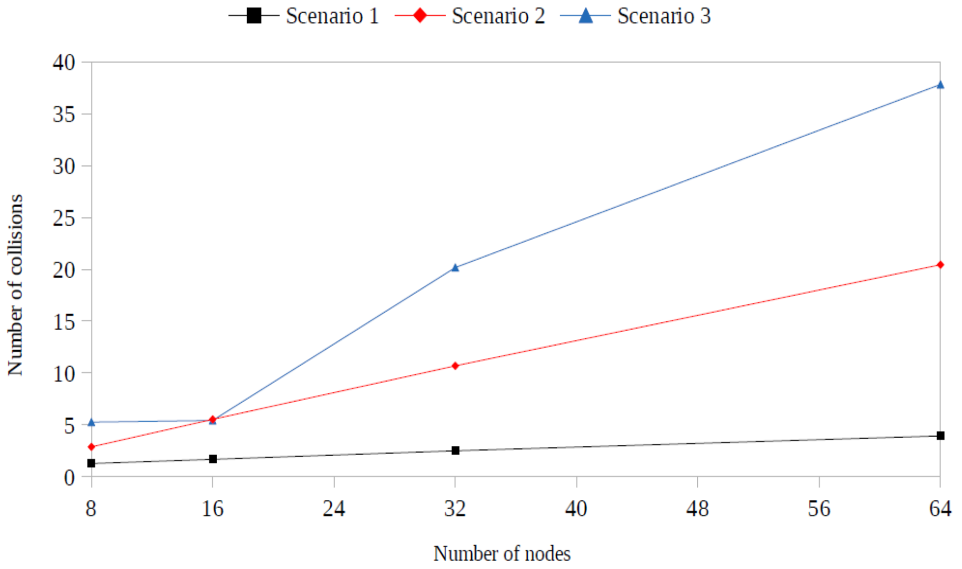


FIGURE 5.2: Comparison results between the three scenarios in terms of the average of the maximum number of collisions.

The evaluation results of these three scenarios show that dividing the superframe into short and fixed lengths of APs, and choosing the *BC* according to our proposed CSMA/CA, increases the number of collisions in the network, especially for networks of a medium and high number of nodes. However, our proposed CSMA/CA enabled us to cut down the number of collisions obtained in the first evaluation of the standard CSMA/CA to more than half.

Average of maximum waiting time

The evaluation results are depicted in Figure 5.3. This Figure represents the comparison results between the three scenarios in terms of the average of the maximum value of waiting time spent by the nodes in idle listening sources.

The evaluation results of these three scenarios show that building the standard CSMA/CA with an important number of idle listening sources, lead to spend more time in these idle listening locations, even with the decrease of the collisions number. This is primarily due to the long periods of the NAPs, as we discussed in Subsection 4.4.2 and Section 4.5.

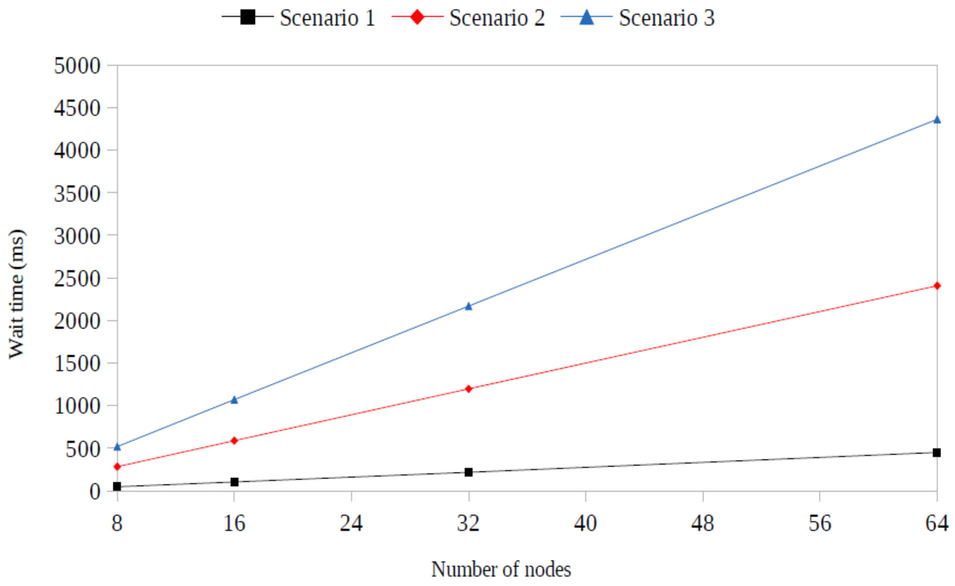


FIGURE 5.3: Comparison results between the three scenarios in terms of the average of the maximum value of waiting time spent by the nodes in the idle listening sources.

Average of maximum successful transmissions

The evaluation results are depicted in Figure 5.4. This Figure represents the comparison results between the three scenarios in terms of the average of the maximum number of packets successfully transmitted.

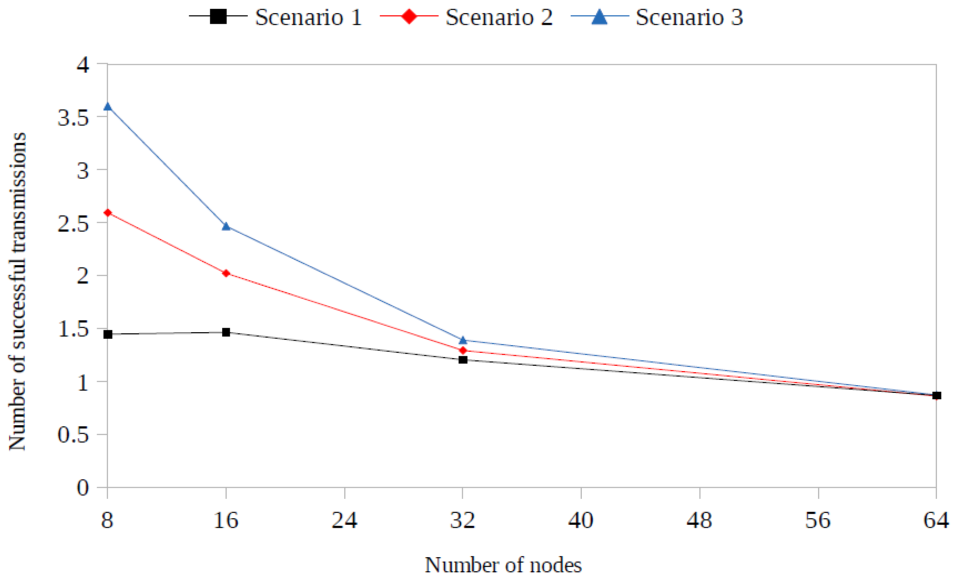


FIGURE 5.4: Successful transmissions comparison results between the three scenarios in terms of the average of the maximum number of packets successfully transmitted.

The evaluation results of these three scenarios show that using a superframe with three APs and decreasing the number of collisions through our proposed CSMA/CA, have a positive impact on the average of the maximum number of packets successfully transmitted, where it exceeds the rate obtained from the evaluation of the standard CSMA/CA.

5.3 Comparison

After having evaluated the performance of the proposed CSMA/CA, we have come out with results that we will compare, in this subsection, with the evaluation results of the standard CSMA/CA.

The comparison results are mentioned in Figures 5.5, 5.6, and 5.7. Figure 5.5, shows that the proposed CSMA/CA has a positive impact on the average of the maximum number of collisions, which impacts positively the performance of the WBAN in terms of energy efficiency. During the communication task of the network, decreasing the number of collisions leads to a decrease in the probability of re-transmission and therefore decreasing energy consumption. Figure 5.7, shows that the proposed CSMA/CA has also a positive impact on the average of the maximum number of packets successfully transmitted. Consequently, the throughput rate increases for the WBAN.

Although, Figure 5.6, shows that the proposed CSMA/CA has a negative impact on the average of the maximum value of waiting time, which increases the delay of transmission for WBAN. This result is due to the high number of idle listening sources of the standard and the proposed CSMA/CA, and the long periods of the non-access phases of the IEEE 802.15.6 superframe.

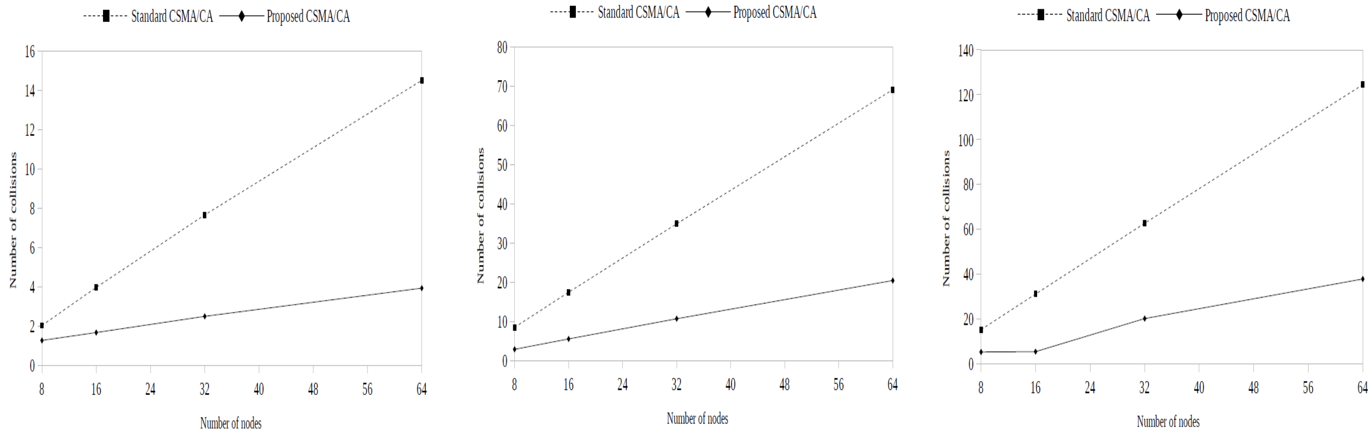
In addition to these results, the Figures 5.5, 5.6, and 5.7, show that for the properties evaluated and with the growth of the network density, the performance of the WBAN degrades, which proofs the non-scalability of the CSMA/CA access method based WBAN. As well, the performance of the WBAN degrades during the superframe duration.

As a result, with our proposed CSMA/CA, we managed to decrease the average of the maximum number of collisions obtained in the first evaluation of the standard CSMA/CA to more than half. This drop led to increase slightly the average of the maximum number of packets successfully transmitted. We notice that (1) dividing the superframe into short and fixed lengths of access phases compared to the long and fixed lengths of non-access phases, and (2) constructing the CSMA/CA access method with a high number of idle listening sources, are still the same problems that degrade the performance of the CSMA/CA access method, and therefore the performance of the WBAN.

5.4 Conclusion

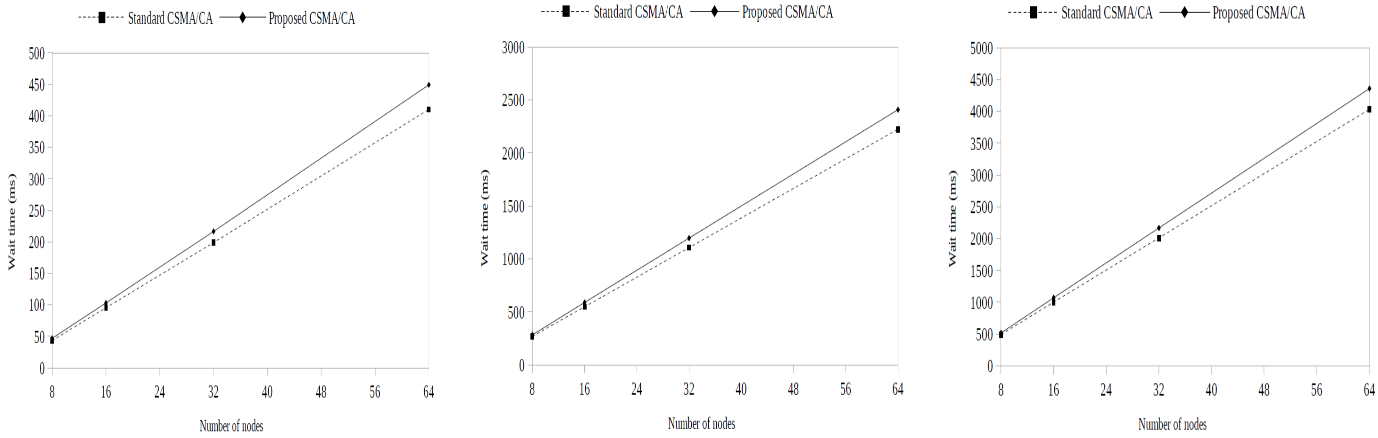
In this chapter, we evaluated the proposed CSMA/CA access method. The evaluation results showed that it has a positive impact on the average of the maximum number of collisions and the maximum number of packets successfully transmitted.

The proposed CSMA/CA access method managed to decrease the number of collisions obtained in the first evaluation of the IEEE 802.15.6 CSMA/CA access method to more than half. Consequently, this drop led to a slight increase in the average of the maximum number of packets successfully transmitted compared to the results obtained in the first evaluation of the IEEE 802.15.6 CSMA/CA access method. However, from both evaluations, we came to confirm that dividing the superframe into short and fixed lengths of access phases and constructing the CSMA/CA access method with the high number of idle listening sources are still the problems that degrade the performance of the CSMA/CA access method and, therefore, the performance of the WBAN.



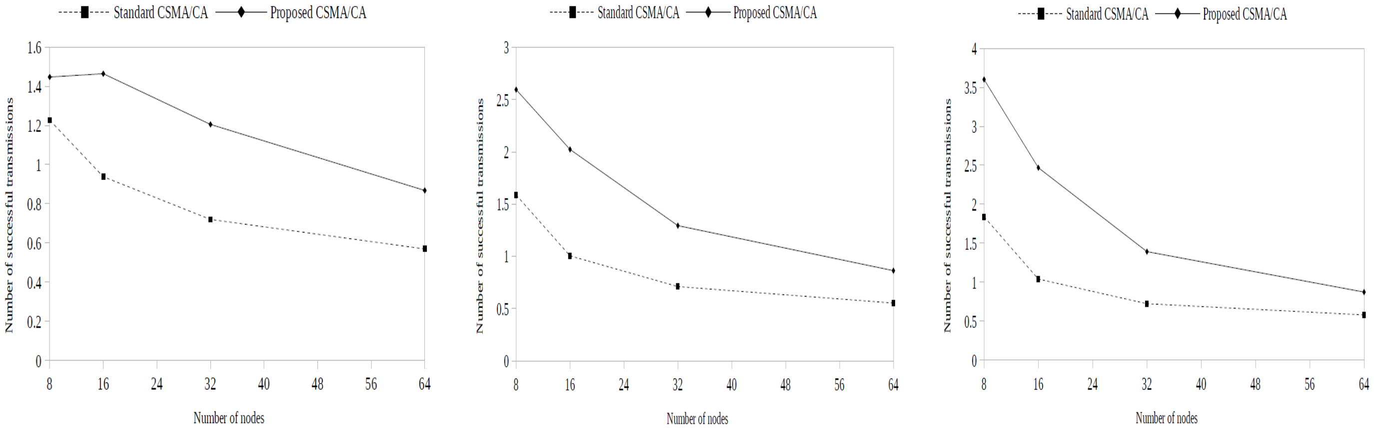
((A)) scenario1 ((B)) scenario2 ((C)) scenario3

FIGURE 5.5: Collisions comparison results between the proposed CSMA/CA and the standard CSMA/CA.



((A)) scenario1 ((B)) scenario2 ((C)) scenario3

FIGURE 5.6: Comparison results between the proposed CSMA/CA and the standard CSMA/CA in terms of the average of the maximum value of waiting time spent by the nodes in idle listening sources.



((A)) scenario1 ((B)) scenario2 ((C)) scenario3

FIGURE 5.7: Successful packets transmissions comparison results between the proposed CSMA/CA and the standard CSMA/CA.

Chapter 6

Toward WBANs MAC Protocols Modeling Language

6.1 Motivation

Modeling and evaluating the behavior of MAC protocols through the stochastic timed automata (STA) and the metric interval temporal logic (MITL) specifications adopted by UPPAAL-SMC necessitate a certain level of expertise. The thing that is not available for many MAC protocol designers. To facilitate the use of UPPAAL-SMC powerful analysis algorithms, we propose to define a model-driven engineering (MDE) approach that uses a modeling method (MM) as a start and the UPPAAL-SMC as a target and back. The stakeholders of this MM are the WBAN communications protocols designers and researchers for the purpose of modeling, simulating, and verifying the behavior of the WBAN communication protocols, especially, MAC protocols. In this chapter, WBAN-MM refers to the modeling method of the WBAN. Figure 6.1, represents the global structure of the WBAN-MM.

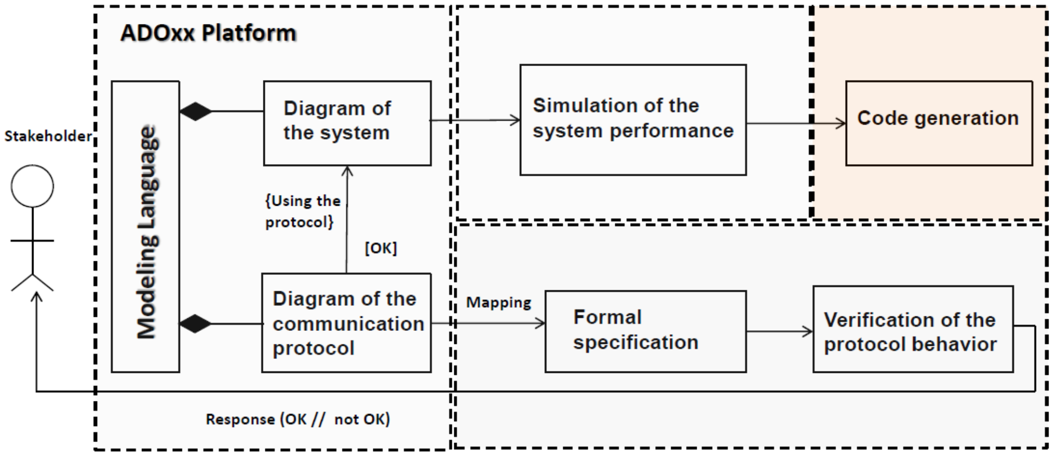


FIGURE 6.1: The WBAN-MM global structure.

6.2 Proposition

Our contribution aims to define an MDE approach that uses the ADOxx platform as a start and the UPPAAL-SMC toolset as a target. To realize this approach, we should define, at first, the Meta-models of our domain-specific modeling language (DSML), domain-specific query language (DSQL), and domain-specific representation (DSR): 1) we create the DSML Meta-models to model the behavior of the MAC protocols. 2) We specify the DSQL Meta-models to check the MAC protocols properties. 3) We create the DSR Meta-models to express the analysis results in an understandable way for the MAC protocols designers. Then, we should introduce the Meta-models of UPPAAL-SMC's STA, Queries, and Traces. Finally, we should model the transformations from the ADOxx models to the UPPAAL-SMC models and back. The Steps involving the construction of our approach are the following:

- Step 1: Creation of the Meta-models of the DSML for modeling the behavior of the MAC protocols.
- Step 2: Introduction of the Meta-models of the UPPAAL-SMC's STA.
- Step 3: Definition of the transformation rules from the DSML to UPPAAL-SMC's STA using the extensible stylesheet language transformations (XSLT).
- Step 4: Specification of the Meta-models of the DSQL to check the MAC protocol properties.
- Step 5: Introduction of the Meta-models of the UPPAAL-SMC Queries.
- Step 6: Definition of the transformation rules from the DSQL to UPPAAL-SMC Queries using a transformation method.
- Step 7: Introduction of the Meta-models of the UPPAAL-SMC Traces that presents the results of the model-checking process. This latter checks if the stochastic timed automata model satisfies the property specified by the Query.
- Step 8: Creation of the Meta-models of the DSR to express the analysis results in an understandable way by the MAC protocols designers.
- Step 9: Definition of the transformation rules from the UPPAAL-SMC Traces models to DSR using a transformation method.

ADOxx Meta-modeling platform (Karagiannis, Mayr, and Mylopoulos, 2016): is an open-source experimentation environment for researchers and practitioners to realize individual Meta-models and model processing functionalities for domain-specific conceptual modeling methods as modeling tools.

Meta-model (Kelly and Tolvanen, 2008): the Meta-model is considered as a specification language-the word "meta" is used because the specification language is one level higher than the usual models. A Meta-model is defined as a conceptual model of a modeling language. It describes the concepts of a language, their properties, the legal connections between language elements, model hierarchy structures, and model correctness rules. The Meta-model is not only important in defining languages but also it is advantageous in systematizing and formalizing weakly defined languages, providing a more "objective" approach to analyzing and comparing languages and examining linkages between modeling languages and programming languages. The Meta-model is also successfully used in building modeling tools, interfaces between tools (e.g., XML), and repository definitions.

According to (Fill and Karagiannis, 2013; Karagiannis, 2015; Karagiannis, Mayr, and Mylopoulos, 2016), conceptualization is a process of realizing a modeling method. This process is divided into five steps or phases forming a lifecycle (or more specifically, the conceptualization Lifecycle). These phases are defined as follows:

- Step 1: The Creation phase uses techniques of knowledge acquisition and requirements elicitation in order to obtain modeling language requirements and the modeling functionality requirements.
- Step 2: The Design phase produces specifications for the Meta-model, the language grammar, and the recommended graphical representation and functionality.
- Step 3: The Formalization phase ensures that the outcome of the previous phase has no ambiguity, either with the purpose of sharing specifications within a community or in preparation for a platform-specific implementation.
- Step 4: The Development phase will produce a modeling prototype or proof of concept on the targeted Meta-modeling platform.
- Step 5: The Deployment/Validation phase deals with packaging and installing the modeling proof of concept and analyzing its user experience and the conformance to modeling requirements.

Based on the conceptualization steps, we start realizing our modeling method. We define in the following the DSML of WBAN that is presented through the name WBAN modeling language (WBAN-ML) to model the behavior of the WBANs MAC protocols.

6.3 WBAN-ML

Our contribution aims to create a simple WBAN-ML that can be used by the WBANs MAC protocols designers and researchers to model the behavior of their proposed WBANs MAC protocols. We propose to use a simple flowchart to model the behavior of MAC protocols. The realization of WBAN-ML requires Meta-models, concepts, and notations. We divide our WBAN-ML into three models of three Meta-models based on the ADOxx Meta-Metamodel, as depicted in Figure 6.2: the WBAN model, the Node model, and the Hub model.

The WBAN model concepts are the external environment, where the body can exist, the body, the nodes and the hub that are placed on the body. The notations used for the WBAN model concepts are the same notations adopted by the WBAN community, as depicted in Figure 6.3. The Meta-model of the WBAN model is defined in Figure 6.5.

The Node model and the Hub model have the same behavior modeling concepts, except that the node has three sensors concepts. The notations used for these concepts are the same notations used for the ordinary flowchart concepts, as depicted in Figure 6.4. The Meta-models of the Node and the Hub models are defined in Figures 6.6 and 6.7, respectively.

We mention that this part is under discussion and modification, the reason for its short description. Figures 6.8, 6.9, and 6.10 represent the prototype implementation results of the WBAN-ML.

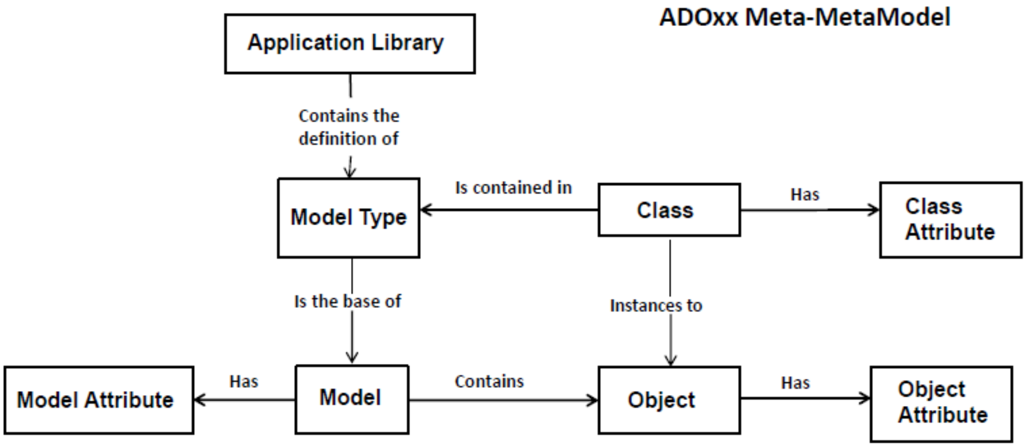


FIGURE 6.2: ADOxx Meta-Metamodel.

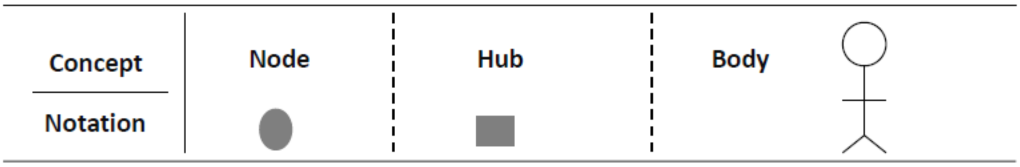


FIGURE 6.3: Concepts and notations of the WBAN model.

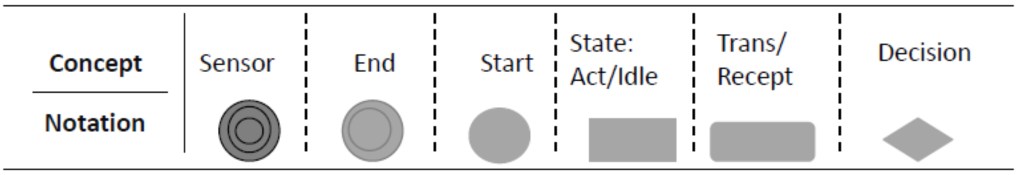


FIGURE 6.4: Concepts and notations of the Node and the Hub models.

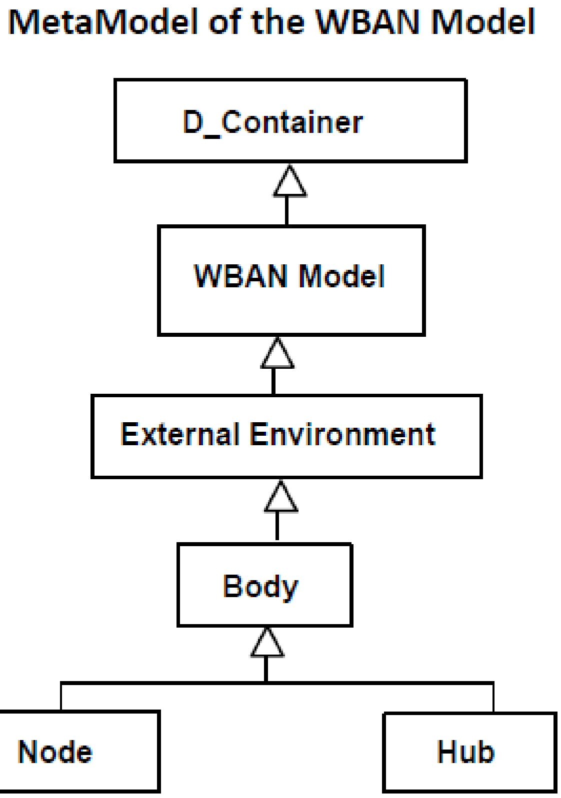


FIGURE 6.5: Meta-model of the WBAN model.

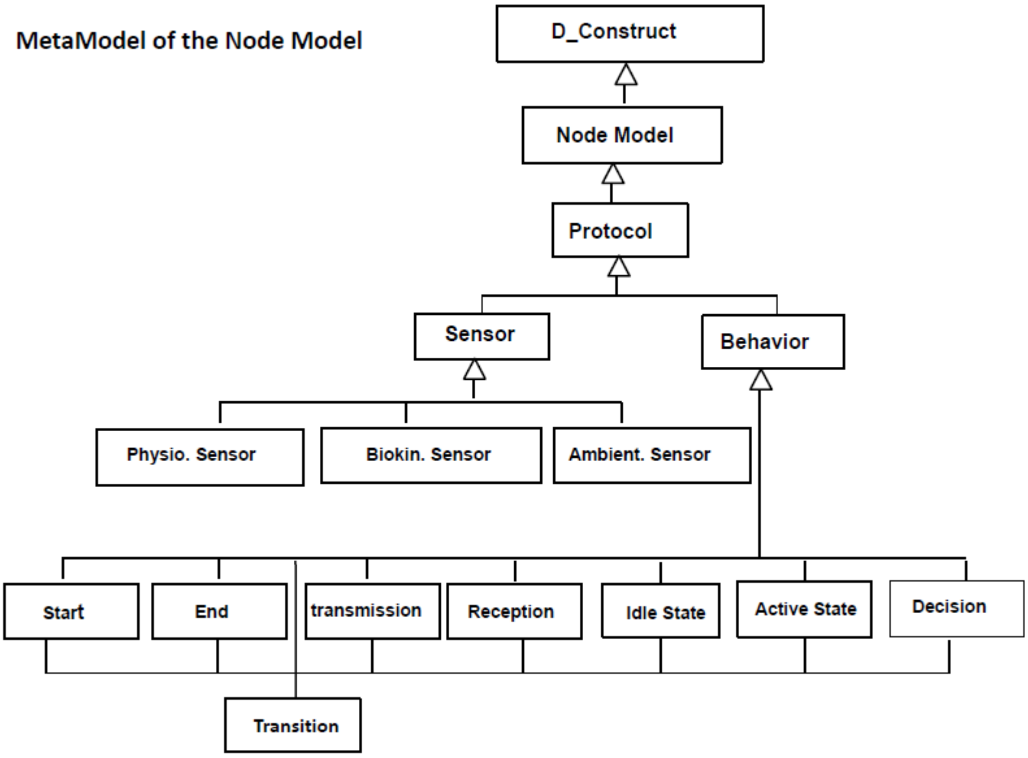


FIGURE 6.6: Meta-model of the Node model.

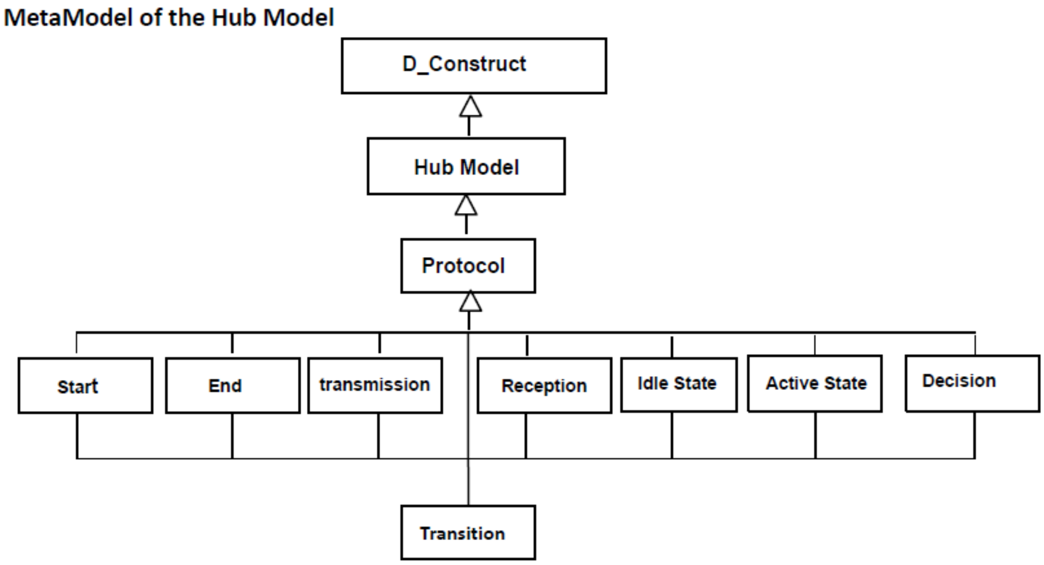


FIGURE 6.7: Meta-model of the Hub model.

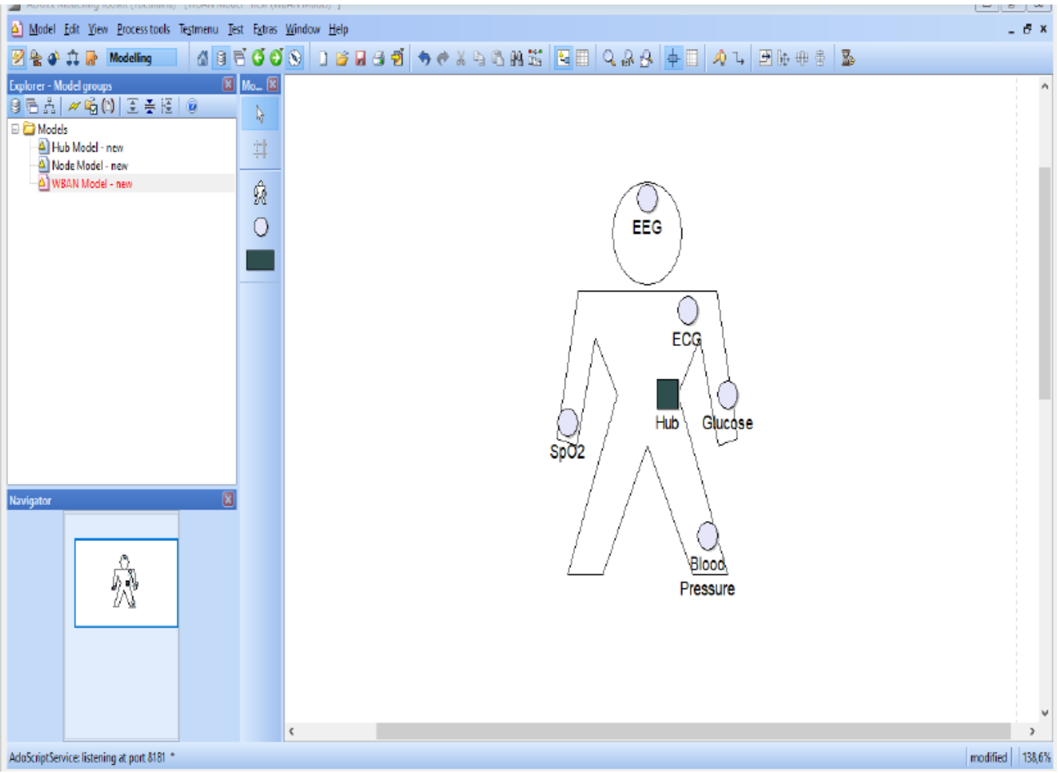


FIGURE 6.8: The WBAN model.

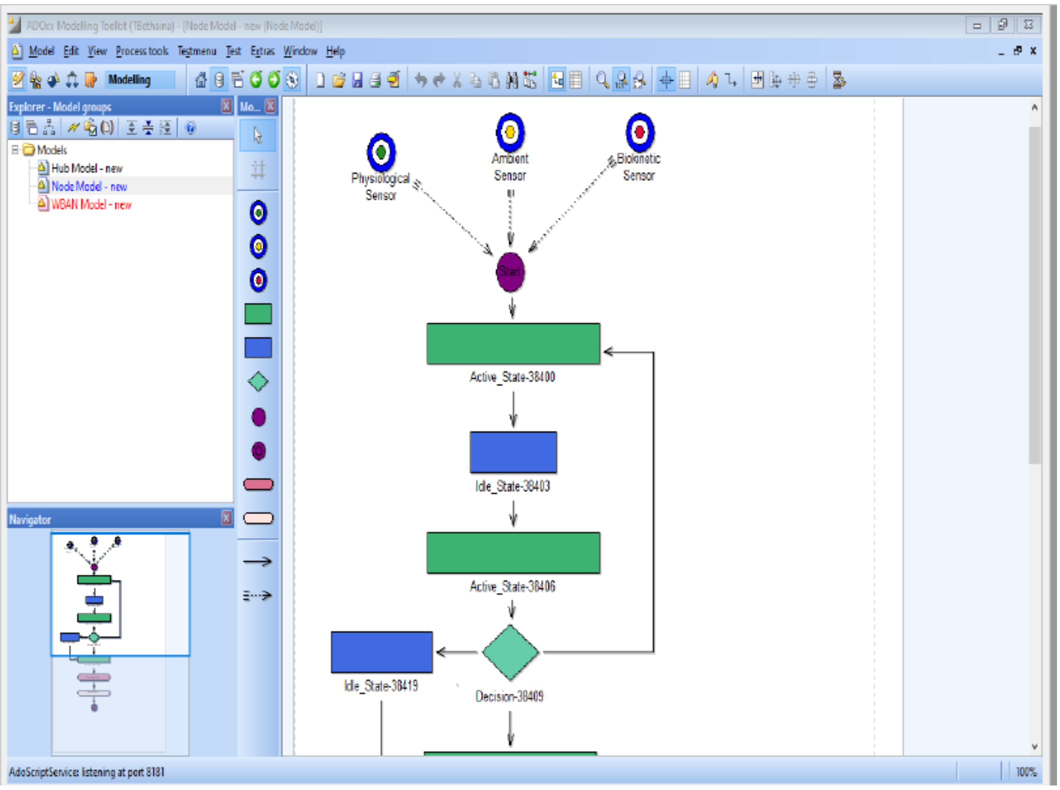


FIGURE 6.9: The Node model.

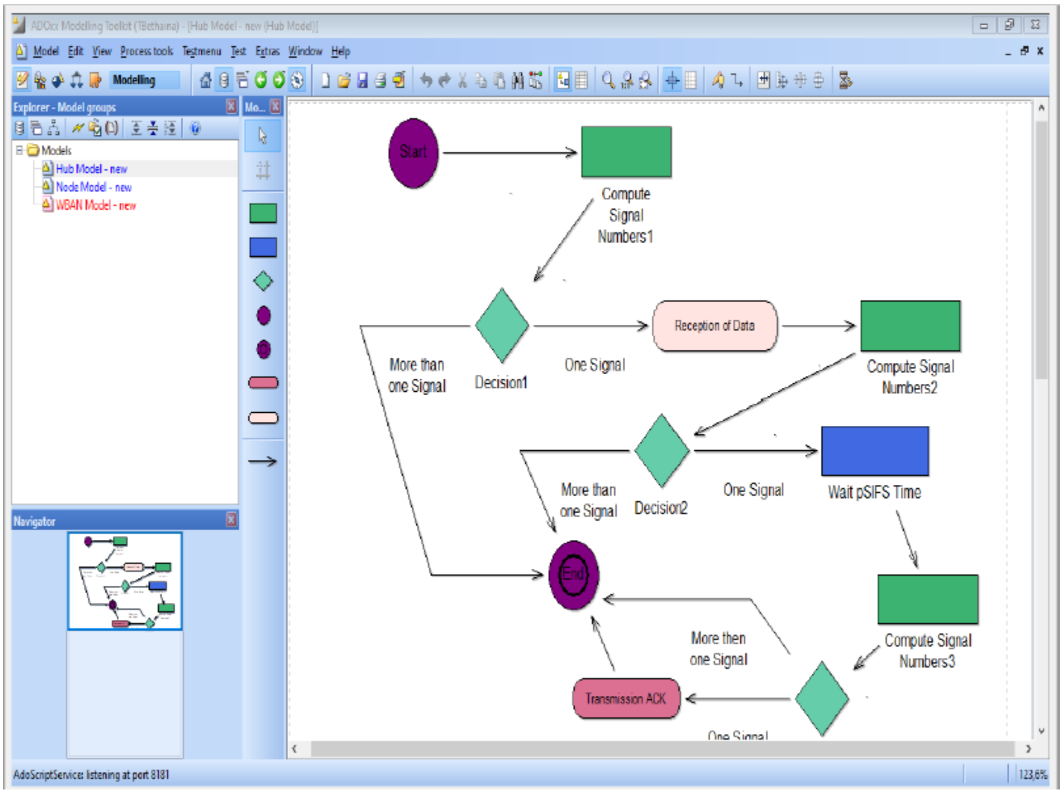


FIGURE 6.10: The Hub model.

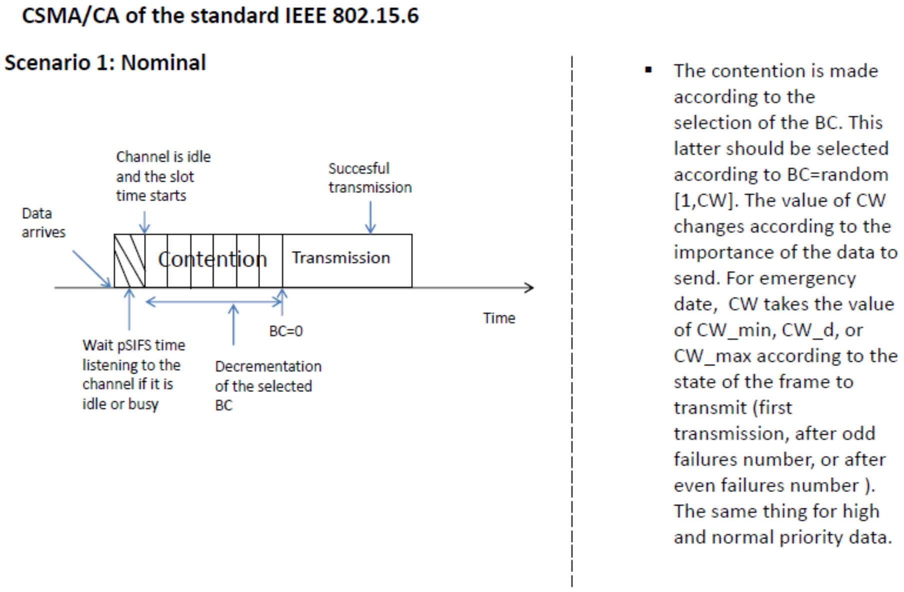
Chapter 7

General Conclusion

In this chapter, we come to conclude that in Chapter 1, we introduced this thesis through context, objectives, plan, and publications. In Chapter 2 we stated the definition, components, communication architecture, requirements and the existing MAC protocols of the WBAN. In addition, we compared the existing MAC protocols of the WBAN and we listed the studies that evaluated and enhanced the performance of the IEEE Standard 802.15.6 CSMA/CA access method. As a result of this detailed review, up to now, there is no MAC protocol that supports all the stringent requirements of WBAN, and there is not a whole performance evaluation or enhancement of the IEEE 802.15.6 CSMA/CA access method. In Chapter 3, we used the statistical model-checking toolset UPPAAL-SMC to investigate the posting access method under the WBAN stochastic environment. Based on UPPAAL-SMC, we modeled and evaluated the behavior of the posting access method in terms of scalability. From the performance evaluation results, we concluded that the hub works with the same performance, even with the increase in the network density. Thus, validating the scalability of the posting access method, and therefore, validating the scalability of the WBAN. In Chapter 4, we evaluated, using the statistical model-checking toolset UPPAAL-SMC, the performance of the IEEE Standard 802.15.6 CSMA/CA access method, with regard to WBAN requirements. Through a case study, we analyzed quantitatively the energy-efficiency, throughput, and delay according to the average of the maximum number of collisions, waiting time in idle listening sources, and packets successfully transmitted. Performance evaluation results showed that under the saturation condition, the short and fixed lengths of the access phases (RAP1, RAP2, and CAP) could not cover the medium and high traffic. The converged contention window (CW) intervals for the user priorities (UP5, UP6, UP7) increase the number of collisions. In addition, idle listening sources lead to spend more waiting time in these locations. Therefore, the performance of the WBAN is impacted negatively in terms of energy-efficiency, throughput, and delay. In Chapter 5, the evaluation results of our proposed backoff counter (BC) selection procedure confirmed its positive impact on the average of the maximum number of collisions and the maximum number of packets successfully transmitted. This proposition managed to decrease the number of collisions obtained in the first evaluation of the IEEE Standard 802.15.6 CSMA/CA access method to more than half. Consequently, this drop led to a slight increase in the average of the maximum number of packets successfully transmitted compared to the results obtained in the first evaluation of the IEEE standard 802.15.6 CSMA/CA access method. However, from both evaluations, we came to confirm that dividing the superframe into short and fixed lengths of access phases and constructing the CSMA/CA access method with a high number of idle listening sources are still the problems that degrade the performance of the CSMA/CA access method and, therefore, the performance of the WBAN. This proposition has an extension that is presented in Appendix A. The proposition of this extension is to minimize the number of idle listening and waiting time periods. As well as, to overcome the collision problems, such as overlapping and overhearing through the introduction of the unique time listening to the channel for each node and the proposition of an adaptive and flexible slot length. From the WBAN modeling method proposition in Chapter 6, we conclude that we implemented the prototype of the WBAN modeling language that should be modified and validated.

Appendix A

IEEE 802.15.6 CSMA/CA Access Method: Optimization



CSMA/CA of the standard IEEE 802.15.6

Scenario 1: Nominal

- The contention is made according to the selection of the BC. This latter should be selected according to BC=random [1,CW]. The value of CW changes according to the importance of the data to send. For emergency date, CW takes the value of CW_min, CW_d, or CW_max according to the state of the frame to transmit (first transmission, after odd failures number, or after even failures number). The same thing for high and normal priority data.

FIGURE A.1: IEEE Standard 802.15.6 CSMA/CA access method.

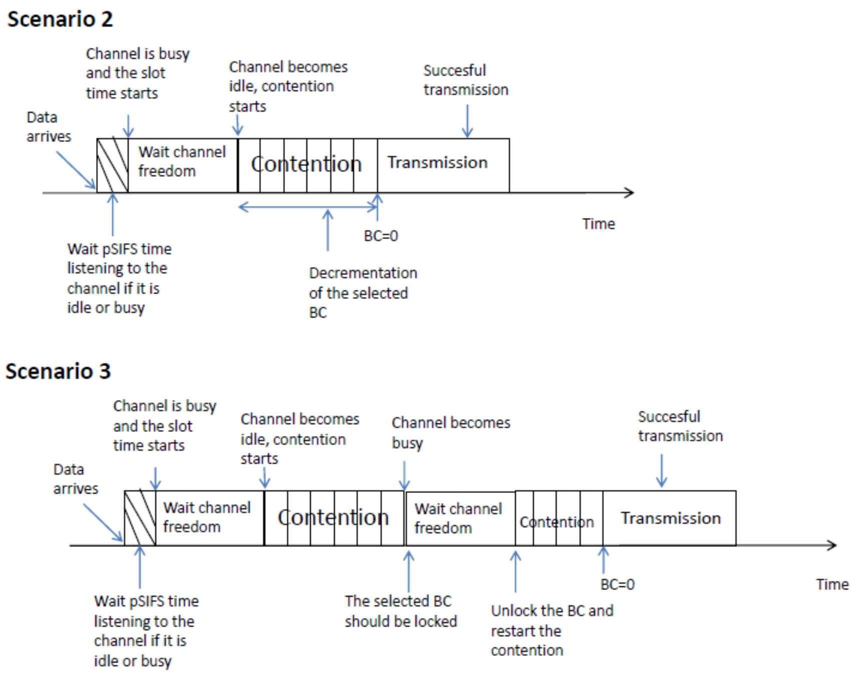
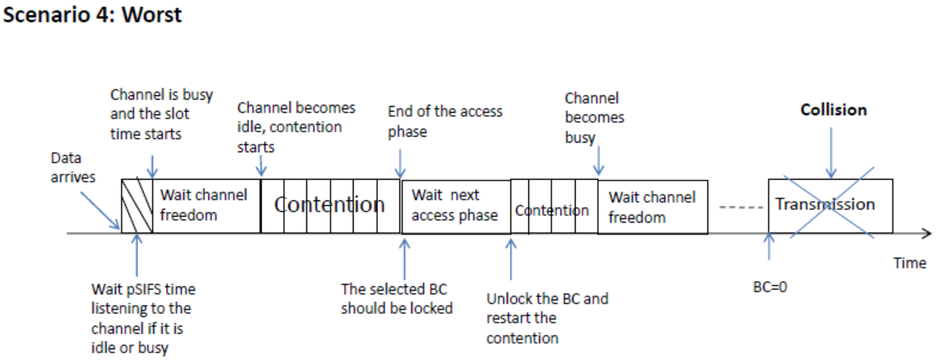


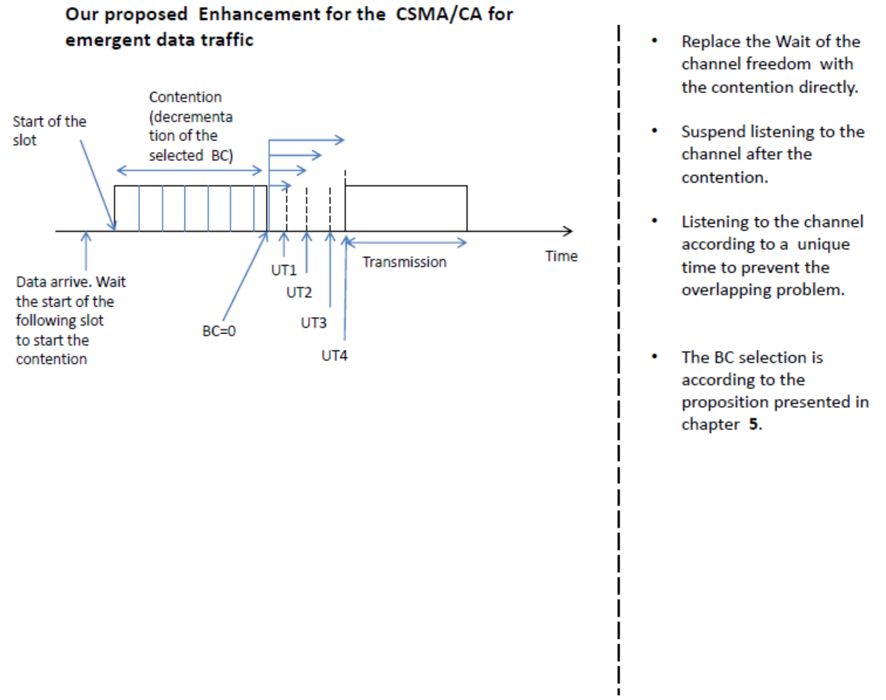
FIGURE A.2: IEEE Standard 802.15.6 CSMA/CA access method.



CSMA/CA limits :

- Waiting the channel freedom
- Waiting the next access phase
- The BC selection intervals
- The pSIFS interval

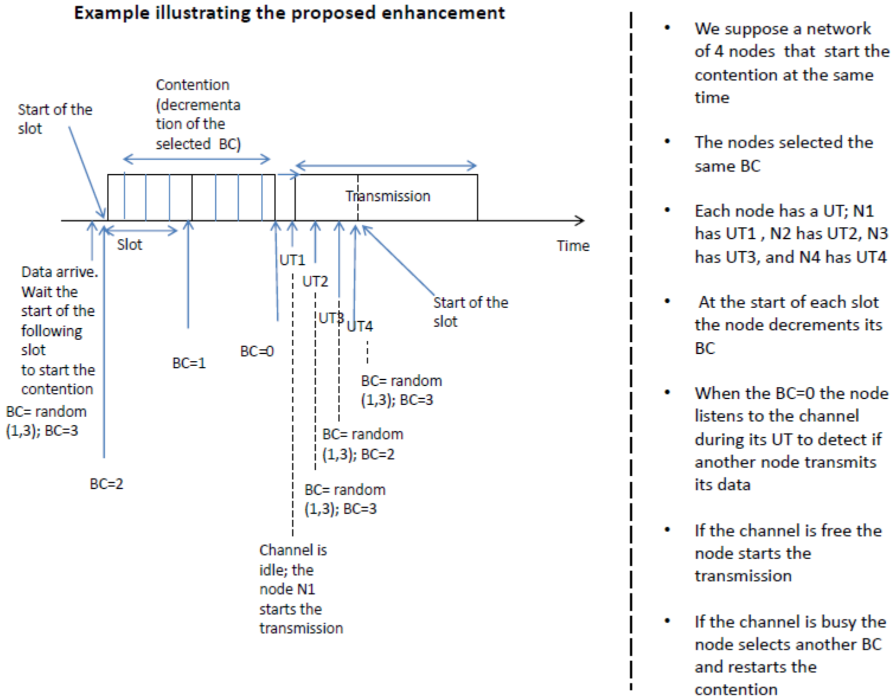
FIGURE A.3: IEEE Standard 802.15.6 CSMA/CA access method.



Our proposed Enhancement for the CSMA/CA for emergent data traffic

- Replace the Wait of the channel freedom with the contention directly.
- Suspend listening to the channel after the contention.
- Listening to the channel according to a unique time to prevent the overlapping problem.
- The BC selection is according to the proposition presented in chapter **5**.

FIGURE A.4: Our proposed CSMA/CA for emergent data traffic.



Example illustrating the proposed enhancement

- We suppose a network of 4 nodes that start the contention at the same time
- The nodes selected the same BC
- Each node has a UT; N1 has UT1 , N2 has UT2, N3 has UT3, and N4 has UT4
- At the start of each slot the node decrements its BC
- When the BC=0 the node listens to the channel during its UT to detect if another node transmits its data
- If the channel is free the node starts the transmission
- If the channel is busy the node selects another BC and restarts the contention

FIGURE A.5: Our proposed CSMA/CA for emergent data traffic: illustration.

Bibliography

Adnan, Muhammad et al. (2020). “Performance Enhancement of IEEE 802.15. 6 Using Collision Avoidance Technique”. In: *Journal of Sensor and Actuator Networks* 9.3, p. 33.

Ahmad, Ashfaq et al. (2014). “iA-MAC: Improved adaptive medium access control protocol for wireless body area networks”. In: *2014 14th International Symposium on Communications and Information Technologies (ISCIT)*. IEEE, pp. 156–160.

Akyildiz, Ian F and Mehmet Can Vuran (2010). *Wireless Sensor Networks*. Vol. 4. John Wiley & Sons. DOI: 10.1002/9780470515181.

Al Ameen, Moshaddique et al. (2012). “A power efficient MAC protocol for wireless body area networks”. In: *EURASIP Journal on Wireless Communications and Networking* 2012.1, pp. 1–17.

Alam, Muhammad Mahtab et al. (2012a). “Latency-energy optimized MAC protocol for body sensor networks”. In: *2012 Ninth International Conference on Wearable and Implantable Body Sensor Networks*. IEEE, pp. 67–72.

— (2012b). “TAD-MAC: Traffic-aware dynamic MAC protocol for wireless body area sensor networks”. In: *IEEE Journal on Emerging and Selected Topics in Circuits and Systems* 2.1, pp. 109–119.

Alur, R and DL Dill (n.d.). *A theory of timed automata (1994) Theoretical Computer Science, 126*.

Alur, Rajeev, Tomás Feder, and Thomas A Henzinger (1996). “The benefits of relaxing punctuality”. In: *Journal of the ACM (JACM)* 43.1, pp. 116–146. DOI: 10.1145/227595.227602.

Alur, Rajeev and Parthasarathy Madhusudan (2004). “Decision problems for timed automata: A survey”. In: *Formal Methods for the Design of Real-Time Systems*. Springer, pp. 1–24. DOI: 10.1007/978-3-540-30080-9_1.

An, Ni et al. (2013). “Performance analysis of CSMA/CA based on the IEEE 802.15. 6 MAC protocol”. In: *2013 15th IEEE International Conference on Communication Technology*. IEEE, pp. 539–544.

Association, IEEE Standards et al. (2012). “IEEE Standard for Local and Metropolitan Area Networks—Part 15.6: Wireless Body Area Networks”. In: *IEEE Standard for Information Technology, IEEE* 802.6, pp. 1–271. DOI: 10.1109/IEEESTD.2012.6161600.

Baier, C (2008). *J-. P. Katoen. Principles of Model Checking*.

Bandyopadhyay, Bitan et al. (2014). “Markov chain based analysis of IEEE 802.15. 6 mac protocol in real life scenario”. In: *Proceedings of the 9th International Conference on Body Area Networks*, pp. 331–337.

Behrmann, Gerd, Alexandre David, and Kim G Larsen (2004). “A tutorial on uppaal”. In: *Formal methods for the design of real-time systems*. Springer, pp. 200–236. DOI: 10.1007/978-3-540-30080-9_7.

Behrmann, Gerd et al. (2007). "Uppaal-tiga: Time for playing games!" In: *International Conference on Computer Aided Verification*. Springer, pp. 121–125. DOI: `10.1007/978-3-540-73368-3\_14`.

Bengtsson, Johan et al. (1995). "UPPAAL—a tool suite for automatic verification of real-time systems". In: *International hybrid systems workshop*. Springer, pp. 232–243. DOI: `10.1007/BFb0020949`.

Benmansour, Tariq, Toufik Ahmed, and Samira Moussaoui (2016). "Performance evaluation of IEEE 802.15. 6 MAC in monitoring of a cardiac patient". In: *2016 IEEE 41st conference on local computer networks workshops (LCN workshops)*. IEEE, pp. 241–247.

Benmansour, Tariq et al. (2020). "Performance analyses of the IEEE 802.15. 6 wireless body area network with heterogeneous traffic". In: *Journal of Network and Computer Applications*, p. 102651.

Bozga, Marius et al. (1998). "Kronos: A model-checking tool for real-time systems". In: *International Symposium on Formal Techniques in Real-Time and Fault-Tolerant Systems*. Springer, pp. 298–302. DOI: `10.1007/BFb0055357`.

Bradai, Nourchene, Lamia Chaari Fourati, and Lotfi Kamoun (2014). "New analytical model for ieee 802.15. 6 under saturation condition and noisy channel". In: *2014 9th International Symposium on Communication Systems, Networks & Digital Sign (CSNDSP)*. IEEE, pp. 243–248.

Cavallari, Riccardo and Chiara Buratti (2014). "On the performance of IEEE 802.15. 6 CSMA/CA with priority for query-based traffic". In: *2014 European Conference on Networks and Communications (EuCNC)*. IEEE, pp. 1–5.

Chen, Min et al. (2011). "Body area networks: A survey". In: *Mobile networks and applications* 16.2, pp. 171–193. DOI: `10.1007/s11036-010-0260-8`.

Clarke, Edmund M (2008). "The birth of model checking". In: *25 Years of Model Checking*. Springer, pp. 1–26.

Clarke, Edmund M and Jeannette M Wing (1996). "Formal methods: State of the art and future directions". In: *ACM Computing Surveys (CSUR)* 28.4, pp. 626–643. DOI: `10.1145/242223.242257`.

Clarke, Edmund M and Paolo Zuliani (2011). "Statistical model checking for cyber-physical systems". In: *International Symposium on Automated Technology for Verification and Analysis*. Springer. Berlin, Heidelberg, pp. 1–12. DOI: `10.1007/978-3-642-24372-1\_1`.

David, Alexandre et al. (2011a). "Statistical model checking for networks of priced timed automata". In: *International Conference on Formal Modeling and Analysis of Timed Systems*. Springer, pp. 80–96. DOI: `10.1007/978-3-642-24310-3\_7`.

David, Alexandre et al. (2011b). "Time for statistical model checking of real-time systems". In: *International Conference on Computer Aided Verification*. Springer, pp. 349–355. DOI: `10.1007/978-3-642-22110-1\_27`.

David, Alexandre et al. (2015). "Uppaal stratego". In: *International Conference on Tools and Algorithms for the Construction and Analysis of Systems*. Springer, pp. 206–211. DOI: `10.1007/978-3-662-46681-0\_16`.

Emerson, E Allen (2008). "The beginning of model checking: A personal perspective". In: *25 Years of Model Checking*. Springer, pp. 27–45. DOI: `10.1007/978-3-540-69850-0\_2`.

Fang, Gengfa and Eryk Dutkiewicz (2009). "BodyMAC: Energy efficient TDMA-based MAC protocol for wireless body area networks". In: *2009 9th international symposium on communications and information technology*. IEEE, pp. 1455–1459.

Fill, Hans-Georg and Dimitris Karagiannis (2013). "On the conceptualisation of modelling methods using the ADOxx meta modelling platform". In: *Enterprise Modelling and Information Systems Architectures (EMISAJ)* 8.1, pp. 4–25.

Fisher, Michael (2011). *An introduction to practical formal methods using temporal logic*. John Wiley & Sons. DOI: 10.1002/9781119991472.

Fourati, Hend, Hanen Idoudi, and Leila Azouz Saidane (2016). "A novel IEEE 802.15. 6 CSMA/CA service differentiation". In: *2016 IEEE/ACS 13th International Conference of Computer Systems and Applications (AICCSA)*. IEEE, pp. 1–7.

— (2018). "Intelligent slots allocation for dynamic differentiation in IEEE 802.15. 6 CSMA/CA". In: *Ad Hoc Networks* 72, pp. 27–43.

Fourati, Hend et al. (2015). "Performance evaluation of ieee 802.15. 6 csma/ca-based canet wban". In: *2015 IEEE/ACS 12th International Conference of Computer Systems and Applications (AICCSA)*. IEEE, pp. 1–7.

Frigo, Guglielmo and Giada Giorgi (2017). "IEEE 802.15. 6 compliant WBSN: a case study". In: *2017 IEEE International Workshop on Measurement and Networking (M&N)*. IEEE, pp. 1–6.

Henzinger, Thomas A, Pei-Hsin Ho, and Howard Wong-Toi (1997). "HyTech: A model checker for hybrid systems". In: *International Conference on Computer Aided Verification*. Springer, pp. 460–463. DOI: 10.1007/3-540-63166-6_48.

Hiep, Pham Thanh, Nguyen Huy Hoang, and Ryuji Kohno (2015). "Performance analysis of multiple-hop wireless body area network". In: *Journal of Communications and Networks* 17.4, pp. 419–427.

Hiep, Pham Thanh, Ryuji Kohno, et al. (2017). "Performance analysis method for IEEE 802.15. 6 based WBANs with adaptive BCH code rates". In: *Wireless Personal Communications* 94.3, pp. 605–619.

Huang, Renwei et al. (2015). "Analysis and comparison of the IEEE 802.15. 4 and 802.15. 6 wireless standards based on MAC layer". In: *International Conference on Health Information Science*. Springer, pp. 7–16.

Ibarra, Ernesto et al. (2015). "HEH-BMAC: Hybrid polling MAC protocol for WBANs operated by human energy harvesting". In: *Telecommunication systems* 58.2, pp. 111–124.

Isikman, Arif Onder et al. (2011). "Body area networks". In: *Mobile Networks and Applications Journal* 16.2, pp. 171–193.

Jinbao, Zhang and Chen Lei (2014). "Energy-efficient multipriority MAC of wireless body area network". In: *2014 XXXIth URSI General Assembly and Scientific Symposium (URSI GASS)*. IEEE, pp. 1–4.

Jung, Byoung Hoon, Raja Usman Akbar, and Dan Keun Sung (2012). "Throughput, energy consumption, and energy efficiency of IEEE 802.15. 6 body area network (BAN) MAC protocol". In: *2012 IEEE 23rd International Symposium on Personal, Indoor and Mobile Radio Communications-(PIMRC)*. IEEE, pp. 584–589.

Karagiannis, Dimitris (2015). "Agile modeling method engineering". In: *Proceedings of the 19th panhellenic conference on informatics*, pp. 5–10.

Karagiannis, Dimitris, Heinrich C Mayr, and John Mylopoulos (2016). *Domain-specific conceptual modeling*. Springer.

Kelly, Steven and Juha-Pekka Tolvanen (2008). *Domain-specific modeling: enabling full code generation*. John Wiley & Sons.

Khan, Pervez, Niamat Ullah, and Hoon Kim (2017). "WBAN MAC Protocols–Non-Saturation Modeling and Performance Analysis." In: *KSII Transactions on Internet & Information Systems* 11.3.

Khan, Pervez et al. (2014). "Analytical modeling of IEEE 802.15. 6 CSMA/CA protocol under different access periods". In: *2014 14th International Symposium on Communications and Information Technologies (ISCIT)*. IEEE, pp. 151–155.

Khan, Pervez et al. (2015). "Performance analysis of WBAN MAC protocol under different access periods". In: *International Journal of Distributed Sensor Networks* 11.10, p. 102052.

Khan, Pervez et al. (2017). "Performance analysis of different backoff algorithms for WBAN-based emerging sensor networks". In: *Sensors* 17.3, p. 492.

Kiesel, W and Pl Kuehn (1983). "A new CSMA-CD protocol for local area networks with dynamic priorities and low collision probability". In: *IEEE Journal on Selected Areas in Communications* 1.5, pp. 869–876. DOI: 10.1109/JSAC.1983.1145982.

Kim, BeomSeok and Jinsung Cho (2012). "A novel priority-based channel access algorithm for contention-based MAC protocol in WBANs". In: *Proceedings of the 6th International Conference on Ubiquitous Information Management and Communication*, pp. 1–5.

Kim, Rae Hyeon, Pyung Soo Kim, and Jeong Gon Kim (2015). "A study on MAC protocol urgent data transmission in wireless bio signal monitoring environment". In: *Advanced Science and Technology Letters* 108, pp. 93–98.

Kumar, Vivek and Bharat Gupta (2016). "Performance Analysis of IEEE 802.15. 6 CSMA/CA Protocol for WBAN Medical Scenario through DTMC Model". In: *Journal of medical systems* 40.12, p. 276.

Kwiatkowska, Marta, Gethin Norman, and David Parker (2002). "PRISM: Probabilistic symbolic model checker". In: *International Conference on Modelling Techniques and Tools for Computer Performance Evaluation*. Springer, pp. 200–204. DOI: 10.1007/3-540-46029-2_13.

Lamine, Elyes et al. (2020). "BPRIM: An integrated framework for business process management and risk management". In: *Computers in Industry* 117, p. 103199.

Larsen, Kim et al. (2001). "As cheap as possible: effcient cost-optimal reachability for priced timed automata". In: *International Conference on Computer Aided Verification*. Springer, pp. 493–505. DOI: 10.1007/3-540-44585-4_47.

Latré, Benoît et al. (2011). "A survey on wireless body area networks". In: *Wireless Networks* 17.1, pp. 1–18. DOI: 10.1007/s11276-010-0252-4.

Li, Changle, H-B Li, and Ryuji Kohno (2009). "Performance evaluation of IEEE 802.15. 4 for wireless body area network (WBAN)". In: *2009 IEEE International conference on communications workshops*. IEEE, pp. 1–5.

Li, Changle et al. (2009). "Scalable and robust medium access control protocol in wireless body area networks". In: *2009 IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*. IEEE, pp. 2127–2131.

Li, Changle et al. (2011). "A novel medium access control protocol with low delay and traffic adaptivity for wireless body area networks". In: *Journal of medical systems* 35.5, pp. 1265–1275.

Li, Changle et al. (2013). "Performance Analysis of IEEE 802.15. 6 MAC Protocol in Beacon Mode with Superframes." In: *KSII Transactions on Internet & Information Systems* 7.5.

Li, Huaming and Jindong Tan (2009). "Heartbeat-driven medium-access control for body sensor networks". In: *IEEE transactions on information technology in biomedicine* 14.1, pp. 44–51.

Liu, Bin, Zhisheng Yan, and Chang Wen Chen (2013). "MAC protocol in wireless body area networks for E-health: Challenges and a context-aware design". In: *IEEE Wireless Communications* 20.4, pp. 64–72.

Marinkovic, Stevan Jovica et al. (2009). "Energy-efficient low duty cycle MAC protocol for wireless body area networks". In: *IEEE Transactions on Information Technology in Biomedicine* 13.6, pp. 915–925.

Mohammadi, Mohammad Sadegh, Qi Zhang, and Eryk Dutkiewicz (2014). "Channel-adaptive MAC frame length in wireless body area networks". In: *2014 International Symposium on Wireless Personal Multimedia Communications (WPMC)*. IEEE, pp. 584–588.

Monowar, Muhammad Mostafa et al. (2012). "McMAC: Towards a MAC protocol with multi-constrained QoS provisioning for diverse traffic in wireless body area networks". In: *Sensors* 12.11, pp. 15599–15627.

Mouradian, Alexandre (2013). "Proposition et vérification formelle de protocoles de communications temps-réel pour les réseaux de capteurs sans fil". PhD thesis. INSA de Lyon.

Movassaghi, Samaneh et al. ((2014)). "Wireless body area networks: A survey". In: *IEEE Communications Surveys & Tutorials* 16.3, pp. 1658–1686. DOI: `10.1109/SURV.2013.121313.00064`.

Omeni, Okundu et al. (2008). "Energy efficient medium access protocol for wireless medical body area sensor networks". In: *IEEE Transactions on biomedical circuits and systems* 2.4, pp. 251–259.

Panunzio, Alfonso et al. (2013). "Experimental characterisation of an IEEE 802.15. 6-based body area network". In: *Proceedings of the 8th International Conference on Body Area Networks*, pp. 116–119.

Rahim, Azizur et al. (2012). "Adaptive-reliable medium access control protocol for wireless body area networks". In: *2012 9th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*. IEEE, pp. 56–58.

Rasheed, Muhammad Babar et al. (2017). "Delay and energy consumption analysis of priority guaranteed MAC protocol for wireless body area networks". In: *Wireless networks* 23.4, pp. 1249–1266.

Rashwand, Saeed and Jelena Misic (2011). "Performance evaluation of IEEE 802.15. 6 under non-saturation condition". In: *2011 IEEE Global Telecommunications Conference GLOBECOM 2011*. IEEE, pp. 1–6.

Rashwand, Saeed and Jelena MišIć (2012). “Effects of access phases lengths on performance of IEEE 802.15. 6 CSMA/CA”. In: *Computer Networks* 56.12, pp. 2832–2846.

Rashwand, Saeed, Jelena Mišić, and Hamzeh Khazaei (2011). “Performance analysis of IEEE 802.15. 6 under saturation condition and error-prone channel”. In: *2011 IEEE Wireless Communications and Networking Conference*. IEEE, pp. 1167–1172.

Rashwand, Saeed, Jelena Mišić, and Vojislav B Mišić (2015). “Analysis of CSMA/CA mechanism of IEEE 802.15. 6 under non-saturation regime”. In: *IEEE Transactions on parallel and Distributed Systems* 27.5, pp. 1279–1288.

Saboor, Abdul et al. (2018). “A unique backoff algorithm in IEEE 802.15. 6 WBAN”. In: *2018 IEEE 88th Vehicular Technology Conference (VTC-Fall)*. IEEE, pp. 1–5.

Saboor, Abdul et al. (2020). “Dynamic Slot Allocation using Non Overlapping Backoff Algorithm in IEEE 802.15. 6 WBAN”. In: *IEEE Sensors Journal*.

Sarkar, Subhadeep et al. (2015). “Performance analysis of IEEE 802.15. 6 MAC protocol under non-ideal channel conditions and saturated traffic regime”. In: *IEEE Transactions on computers* 64.10, pp. 2912–2925.

Schmidt, Robert et al. (2002). “Body Area Network BAN–a key infrastructure element for patient-centered medical applications”. In.

Shankar, Anagha V and Lillykutty Jacob (2016). “A Game theoretic approach for performance enhancement of IEEE 802.15. 6 based WBAN”. In: *2016 International Conference on Signal Processing and Communication (ICSC)*. IEEE, pp. 37–42.

Shu, Minglei et al. (2015). “Modeling and Performance Analysis of MAC Protocol for WBAN with Finite Buffer.” In: *KSII Transactions on Internet & Information Systems* 9.11.

Singh, Shivam Rohit Kumar and Bharat Gupta (2018). “Performance Evaluation of Quality of Service Parameters for Stationary and Moving Body in Wireless Body Area Networks”. In: *2018 IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS)*. IEEE, pp. 1–6.

Touijer, Bethaina, Yann Ben Maissa, and Salma Mouline (2017). “MAC protocols for Wireless Body Area Networks: An overview”. In: *Wireless Communications and Mobile Computing Conference (IWCMC), 2017 13th International*. IEEE. Valencia, Spain, pp. 1227–1232. DOI: `10.1109/IWCMC.2017.7986460`.

— (2020). “Scalability Validation of the Posting Access Method through UPPAAL-SMC Model-Checker”. In: *International Journal of Advanced Computer Science and Applications* 11.8.

— (2021). “IEEE 802.15. 6 CSMA/CA access method for WBANs: Performance evaluation and new backoff counter selection procedure”. In: *Computer Networks* 188, p. 107759.

Toumanari, Ahmed, Rachid Latif, et al. (2014). “Performance analysis of IEEE 802.15. 6 and IEEE 802.15. 4 for wireless body sensor networks”. In: *2014 International Conference on Multimedia Computing and Systems (ICMCS)*. IEEE, pp. 910–915.

Ullah, Sana, Min Chen, and Kyung Sup Kwak (2012). “Throughput and delay analysis of IEEE 802.15. 6-based CSMA/CA protocol”. In: *Journal of medical systems* 36.6, pp. 3875–3891.

Ullah, Sana, Muhammad Imran, and Mohammed Alnuem (2014). “A hybrid and secure priority-guaranteed MAC protocol for wireless body area network”. In: *International Journal of Distributed Sensor Networks* 10.2, p. 481761.

Ullah, Sana and Kyung Sup Kwak (2011). “Throughput and delay limits of IEEE 802.15. 6”. In: *2011 IEEE Wireless Communications and Networking Conference*. IEEE, pp. 174–178.

— (2012). “An ultra low-power and traffic-adaptive medium access control protocol for wireless body area network”. In: *Journal of medical systems* 36.3, pp. 1021–1030.

Ullah, Sana and Eduardo Tovar (2015). “Performance analysis of IEEE 802.15. 6 contention based MAC protocol”. In: *2015 IEEE International Conference on Communications (ICC)*. IEEE, pp. 6146–6151.

Upadhayay, Shravan Kumar and Mansi Gupta (2015). “LEC-TMAC: Improving Energy Consumption & Latency in TMAC Protocol for Wireless Body Area Network”. In: *TELKOMNIKA Indonesian Journal of Electrical Engineering* 15.3, pp. 430–435.

Wang, Farn (2004). “Formal verification of timed systems: A survey and perspective”. In: *Proceedings of the IEEE* 92.8, pp. 1283–1305. DOI: `10.1109/JPROC.2004.831197`.

Xia, Feng and Azizur Rahim (2015). *MAC protocols for cyber-physical systems*. Springer.

Yu, Daeun and Namgi Kim (2016). “An efficient low-power MAC protocol for wireless body sensor networks”. In: *International Journal of Future Generation Communication and Networking* 9.7, pp. 257–268.

Yu, Jeongseok et al. (2016). “Cor-MAC: Contention over reservation MAC protocol for time-critical services in wireless body area sensor networks”. In: *Sensors* 16.5, p. 656.

Yuan, Jingjing, Changle Li, and Wu Zhu (2013). “Energy-efficient MAC in wireless body area networks”. In: *2013 international conference on information science and technology applications (ICISTA-2013)*. Atlantis Press, pp. 21–24.

Zhang, Rongrong, Hassine Moungla, and Ahmed Mehaoua (2015). “Delay analysis of IEEE 802.15. 6 CSMA/CA mechanism in duty-cycling WBANs”. In: *2015 IEEE Global Communications Conference (GLOBECOM)*. IEEE, pp. 1–6.

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CENTRE D’ETUDES DOCTORALES - SCIENCES ET TECHNOLOGIES

Résumé

Cette thèse porte sur l'évaluation des performances des protocoles de contrôle d'accès au support (MAC) pour le réseau de capteurs corporel sans fil (WBAN) par le biais des méthodes de la vérification formelle. L'importance des WBAN a incité les chercheurs à proposer de nouveaux protocoles MAC afin de satisfaire les exigences des WBAN, ce qui nous a conduits à élaborer, dans un premier travail, une analyse comparative, quantitative et qualitative, des protocoles MAC existants pour les WBAN. Selon nos résultats de comparaison, le protocole MAC de la norme IEEE 802.15.6 prend en compte la majorité des exigences des WBAN. Pour valider l'utilité de ce protocole pour les WBAN, nous avons proposé d'évaluer, comme partie centrale de cette thèse, ses performances par une analyse formelle. Nous avons évalué les performances de ses méthodes d'accès Posting et CSMA/CA via le Model-Checker UPPAAL-SMC. Ensuite, nous avons amélioré les performances de la méthode d'accès CSMA/CA en termes de compteur d'attente (BC) et de fenêtre de contention (CW). Le Model-Checker UPPAAL-SMC peut fournir une interprétation stochastique du comportement stochastique des systèmes complexes et temps réel, tels que les WBAN. La modélisation et l'évaluation du comportement des protocoles MAC via les spécifications des automates temporisés stochastiques (STA) et de la logique temporelle d'intervalle métrique (MITL) adoptées par UPPAAL-SMC, nécessitent un certain niveau d'expertise. La chose qui n'est pas disponible pour de nombreux concepteurs de protocoles MAC. Pour faciliter l'utilisation des puissants algorithmes d'analyse d'UPPAAL-SMC, nous avons proposé de définir un prototype d'une approche d'ingénierie dirigée par les modèles (MDE) qui utilise un langage de modélisation spécifique au domaine (DSML) comme point de départ et UPPAAL-SMC comme cible.

Mots-clefs (7) : Réseau de capteurs corporel sans fil, Contrôle d'accès au support, Norme IEEE 802.15.6, CSMA/CA, Vérification formelle, UPPAAL-SMC, Ingénierie dirigée par les modèles.

Abstract

This thesis focuses on the performance evaluation of medium access control (MAC) protocols for the wireless body area network (WBAN) through formal verification methods. The importance of WBANs encouraged the researchers to propose new MAC protocols to satisfy the WBAN requirements, the thing that led us to elaborate, as a first work, a quantitative and qualitative comparative analysis of the existing MAC protocols for WBANs. According to our comparison results, the MAC protocol of the IEEE Standard 802.15.6 considers most of the WBAN requirements. To validate its usefulness for the WBAN, we proposed to evaluate, as the thesis's central part, its performance through formal analysis. We evaluated the performance of its Posting and CSMA/CA access methods through the model-checker UPPAAL-SMC. Then, we enhanced the performance of the CSMA/CA access method in terms of the backoff counter (BC) and the contention window (CW). The model-checker UPPAAL-SMC can provide a stochastic interpretation of the stochastic behaviour of complex and real-time systems, such as WBANs. Modelling and evaluating the behaviour of MAC protocols through the stochastic timed automata (STA) and the metric interval temporal logic (MITL) specifications adopted by UPPAAL-SMC, necessitate a certain level of expertise. The thing that is not available for many MAC protocol designers. To facilitate the use of UPPAAL-SMC powerful analysis algorithms, we proposed to define a prototype of a model-driven engineering (MDE) approach that uses a domain-specific modelling language (DSML) as a start and the UPPAAL-SMC as a target.

Keywords (7): Wireless body area network, Medium access control, IEEE Standard 802.15.6, CSMA/CA, Formal verification, UPPAAL-SMC, Model-driven engineering.