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Adaptive Medium Access Control for Internet-of-Things-Enabled MANETs

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Synonyms

Adaptive channel access control; Contention-based and contention-free channel access; Distributed transmission coordination; QoS-aware hybrid medium access control (MAC)

Definitions

Adaptive medium access control (MAC) for Internet-of-Things (IoT)-based ad hoc networking refers to a distributed (infrastructure-less) link-layer mechanism to coordinate channel access for data transmissions from a varying number of IoT devices, generating either delay-sensitive services or data-hungry applications. The adaptive MAC should achieve and maintain high performance for heterogeneous services with differentiated quality-of-service (QoS) requirements (e.g., delay and throughput) in network traffic load dynamics.

Background and Key Applications

Next-generation wireless networks are envisioned to interconnect a proliferation of Internet-of-Things (IoT) devices (e.g., smartphones, smart sensors and actuators, home appliances) to achieve seamless communication interaction and diversified service customization, such as smart cities, industrial automation, and intelligent transportation (Gubbi et al. 2013). To support an increasing number of end devices, current communication infrastructures are required to be boosted extensively with additional installation and operational cost. In the scenarios where the network infrastructures are temporarily not in place or not accessible (e.g., in hotspot areas or postdisaster areas), mobile ad hoc networking is an infrastructure-less and cost-effective networking technology to connect a large number of IoT devices via a device-to-device (D2D) communication mode (Nishiyama et al. 2015). In mobile ad hoc networks (MANETs), nodes are self-organized and initiate transmission requests over a common wireless channel (with 20MHz bandwidth at 2.4GHz or 5.9GHz spectrum frequencies) in a distributed way. To achieve consistently high link-layer performance (low packet transmission delay and high data throughput), an efficient medium access control

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(MAC) mechanism is required to coordinate channel access from a group of end devices by adapting to the variation of network traffic load (Natkaniec et al. 2013).

Without relying on centralized transmission coordination and device synchronization, the carrier sensing multiple access with collision avoidance (CSMA/CA)-based IEEE 802.11 distributed coordination function (DCF) (Bianchi 2000) is the most commonly used MAC scheme in existing MANETs, where packet transmissions from each node are initiated based on channel contention with an exponential backoff mechanism employed for collision avoidance. The contention-based DCF has the advantage of simplified implementation and high channel utilization in low traffic load conditions (i.e., the number of devices is low). However, its performance degrades substantially when the number of nodes becomes high, since a large portion of channel time is wasted in collided packet transmissions and collision resolution. Distributed time division multiple access (TDMA) schemes (Kanzaki et al. 2003; Wilson et al. 1993) eliminate transmission collisions by allocating time slot(s) exclusively for each device and thus achieve high resource utilization in high network load conditions. However, the control information exchange among devices for distributed time slot acquisition makes the performance of TDMA inferior to DCF in a low network condition. Due to the performance trade-off between contention-based MAC and reservation-based time slot allocation, hybrid MAC schemes are proposed to combine the advantages of both types of MAC schemes by switching between contention-based and contention-free MAC frame structures, either periodically (Zhang et al. 2010, 2011) or adaptively based on instantaneous network load conditions (Hu et al. 2011). For most existing hybrid MAC schemes, the MAC switching decision is made upon measurement of some MAC parameters (e.g., number of idle TDMA slots (Ahmed 1997), number of lost acknowledgments (ACKs) (Hu et al. 2011), node buffer occupancy (Doerr et al. 2005)) which reflect the current network load condition. However, it is difficult to establish an analytical model between those measurement parameters and certain performance metrics (e.g., network throughput and packet delay), thus making the MAC switching decisions not optimal.

To satisfy differentiated quality-of-service (QoS) requirements from heterogeneous IoT services, the distributed MAC is expected to be both context-aware and service-aware (or QoS-aware) in a changing network environment. For example, delay-sensitive voice communications and remote control applications have stringent delay bound requirements on each transmitted packet so that the packets that are received beyond the delay bound are dropped, whereas the smart sensing applications collect data from a massive number of end devices which are throughput-oriented. Service prioritized contention schemes (e.g., busy tone-based MAC (Wang et al. 2007)) give guaranteed channel access opportunities to voice devices to relieve their contention collisions with data devices, which, on the other hand, suppress the data traffic channel access probability. Moreover, packet collisions among voice devices exist and are accumulated with the increase of voice device number. Existing distributed TDMA mechanisms can alleviate channel contention collisions but are not suitable for supporting heterogeneous services. Since most of the data-hungry sensing applications generate event-driven data traffic, the allocated time slots can be underutilized and need to be adaptive to traffic burstiness. To meet differentiated QoS demands, an adaptive and QoS-aware hybrid MAC scheme is required to differentiate the channel access between delay-sensitive applications and high data rate applications, where time slots are allocated to delay-sensitive traffic and data nodes occupy portions of channel time via contention to exploit traffic multiplexing gain (Zhang et al. 2010, 2011). With a varying heterogeneous network traffic load, how to adaptively allocate time slots to delay-sensitive applications and adjust the channel access parameters among data devices to achieve consistently bounded packet loss rate and maximum data throughput needs investigation.

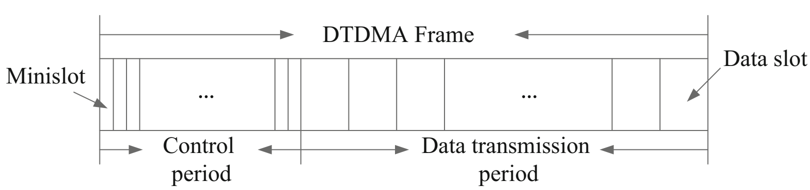
Adaptive MAC Solutions

As stated precedingly, adaptive and hybrid MAC solutions are desired to coordinate packet transmissions among devices in an IoT-based MANET for achieving consistently maximum network performance, by adapting to a varying number of end devices and providing differentiated QoS guarantee. In the following, the technical steps to develop adaptive MAC solutions are presented for a homogeneous service scenario (i.e., support only high-rate data service) and for a heterogeneous service scenario (i.e., support both voice and data applications), respectively.

Homogeneous Service Scenario

Consider a fully connected MANET (i.e., each device is within the one-hop transmission range of any other device.) with a single and error-free wireless channel. Note that developing an adaptive MAC solution for a multi-hop MANET is considered in one of our recent works Ye and Zhuang (2017a). There is no central controller in the network, and devices coordinate their packet transmissions in a distributed manner. Packet transmission failures are due to channel contention collisions. All devices in the network are assumed homogeneous, generating the same type of high-rate data application. Each device randomly chooses its destination among other devices and can send packets to and receive packets from other devices in the half-duplex mode. Every device has a unique device identifier (ID) that is randomly selected and included in its transmitted packet headers. Devices are synchronized in time by receiving an 1PPS signal periodically with a global positioning system (GPS) receiver. The total number of devices in the network is denoted by N, which varies slowly when devices move in or move out the network coverage area. Traffic arrivals at each device are assumed to follow a Poisson process with the rate parameter λ packet/s.

To establish an adaptive MAC framework in the presence of a varying number of devices, a hybrid MAC solution (Ye et al. 2016) is proposed to switch MAC frame structures between the CSMA/CA-based IEEE 802.11 DCF and a dynamic TDMA (DTDMA) scheme (Wilson et al. 1993) under different network load conditions. The DCF with exponential backoff for collision resolution achieves high data throughput when the number of devices is low, but experiences low channel utilization as the transmission collisions are accumulated in high network load conditions. For the DTDMA, time is divided into a sequence of frames, as shown in Fig. 1. Each frame consists of a control period and a data transmission period. The control period has a number of constant-duration minislots used for local information exchange to allocate time slots in the data transmission period to each device. The time slot allocation is conducted in a distributed way to fit the MANET scenario. The number of minislots indicates the maximum number of end devices that can be admitted in the network. The data transmission period is composed of a number of data slots, which equals the current device number in the network, and the duration of each data slot is set the same as one data packet length. We assume that all data packets have an identical and fixed packet length. Since the DTDMA eliminates packet transmission collisions, its performance is superior to the DCF in a high network load condition. Therefore, with the consideration of these two candidate MAC schemes, the proposed



Adaptive Medium Access Control for Internet-of-Things-Enabled MANETs, Fig. 1 A DTDMA frame structure adaptive MAC solution uses a separate mediating MAC entity (Doerr et al. 2005) working on top of the MAC candidates maintained at each device to make MAC switching decisions according to the variation of the number of devices, N, in the network.

To maintain consistently maximum network throughput by switching between the MAC candidates, the optimal MAC switching threshold (i.e., the optimal number of devices N^*) needs to be determined. To this end, a unified and closed-form performance analytical framework (Ye et al. 2016) is established for the aggregate network throughput with respect to the number of devices N for both DCF and DTDMA schemes, based on *least-squares curve fitting* and *M/G/1 queueing analysis*. For the throughput analysis, both traffic non-saturation (i.e., the transmission buffer of each device can be empty) and traffic saturation (i.e., each device always has packets to be transmitted) conditions are considered. For a traffic non-saturation condition, closed-form throughput analytical expressions $H_1(N, \lambda)$ and $H_2(N, \lambda)$ are established in a function of N and λ for the DCF and the DTDMA, respectively. With the increase of N, packet service rate for each device decreases, making the network operating in DCF or DTDMA enter the traffic saturation state. Thus, the throughput for the DCF and the DTDMA is also analyzed in a closed-form function of N, denoted by $H_3(N)$ and $H_4(N)$.

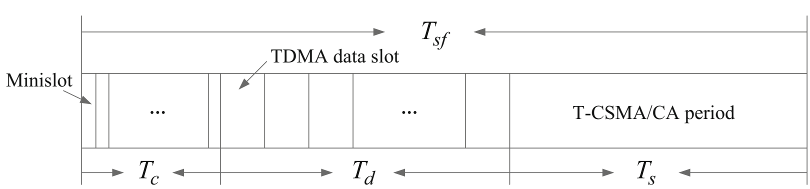
To calculate the optimal MAC switching threshold, denoted by N^*, throughput comparison between the two MAC candidates is conducted based on the developed closed-form performance analytical models. Since DCF and DTDMA have different network load points to enter the traffic saturation state, the following four combinations of traffic load states for both MAC schemes should be taken into consideration for the performance comparison: (1) the network is in the traffic saturation state for both MAC schemes; (2) the network is in a traffic non-saturation state for both MAC schemes; (3) the network is saturated for the DCF and non-saturated for the DTDMA; and (4) the network is saturated for the DTDMA and non-saturated for the DCF. Then, the optimal MAC switching threshold in terms of the number of devices, N^*, in the network can be determined, which also varies with the traffic arrival statistics λ at each device. Therefore, the adaptive MAC solution consistently makes the MAC switching decision at an optimal point (i.e., the DCF is operated when $N < N^*$ and is switched to the DTDMA when $N \geq N^*$) to achieve maximum aggregate network throughput.

Heterogeneous Service Scenario

To support heterogeneous service types, an adaptive and QoS-aware MAC solution is required. Consider the same system model as in the homogeneous service scenario except that both delay-sensitive voice devices and high-rate data devices are present in the network. The number of voice and data devices are denoted by N_v and N_d, which are slowly varying with time. For the delay-sensitive voice service, packet arrivals at each voice device follow an *on/off* model (Wang et al. 2007), which is a two-state Markov process with the *on* and *off* states being the traffic generation and traffic suppression phases, respectively. The durations each device stays in *on* and *off* states are independent and exponentially distributed with respective average of $\frac{1}{\gamma}$ and $\frac{1}{\delta}$. During the *on* state, packets arrive periodically with the constant rate α packet/s. Each voice packet has a hard delay bound requirement, so that packets received beyond the delay bound are dropped. Therefore, the voice service has a packet loss rate bound requirement denoted by P_l. For the data service, each device is expected to access the channel by exploiting resource multiplexing gain to achieve as high as possible data throughput. All data devices are assumed in the traffic saturation state.

To satisfy the QoS requirements from both voice and data services, a QoS-aware hybrid MAC scheme is proposed to differentiate the channel access among voice and data devices (Ye and Zhuang 2017b), where voice devices are allocated time slots in a distributed way to guarantee a bounded packet delay by avoiding contention collisions and data devices contend for the channel access according to a truncated CSMA/CA (T-CSMA/CA) scheme to exploit high resource multiplexing gain. Time is partitioned into a sequence of fixed-duration superframes, as shown in Fig. 2. The duration of each superframe, denoted by T_{sf}, is set the same as the packet delay bound for voice traffic. Each superframe is composed of a control period, a TDMA period, and a T-CSMA/CA period, the durations of which are denoted by T_c, T_d, and T_s. The control period consists of a number N_{mi} of constant-duration minislots, each with an exclusive minislot sequence number (MN). Each voice device selects a unique minislot to broadcast and exchange its local information among its one-hop neighbors for distributed data time slot scheduling in the following TDMA period. Thus, N_{mi} also indicates the maximum number of voice devices (i.e., voice capacity) that can be admitted in the network. The TDMA period is divided into multiple equal-duration data transmission slots, each of which has a unique data slot sequence number (DN). Every active voice node (i.e., having non-empty transmission buffer) occupies one data slot to send a number of packets (a voice burst) generated during the previous superframe time. The number of voice bursts scheduled in each TDMA period is indicated by N_{sv}. To provide voice traffic guaranteed service quality, a maximum fraction $\rho\,(<\ 1)$ of channel time in each superframe is allocated to voice traffic, including the control period and the TDMA period. The voice capacity N_{mi} can be determined based on ρ and the packet loss rate bound P_l. In the T-CSMA period, data devices contend the channel according to the CSMA/CA with exponential backoff with periodic interruption of the control period and the TDMA period in each superframe.

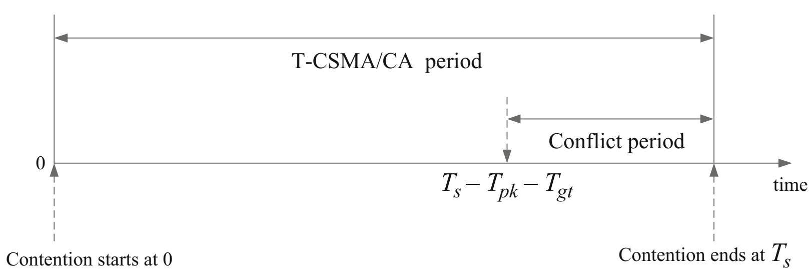
Next, a traffic-adaptive time slot allocation mechanism is presented according to instantaneous voice traffic load in the network. Each voice device randomly selects a minislot from the control period of a superframe after the time synchronization and broadcasts a control packet in the selected minislot to its one-hop neighbors. A control packet sent from a tagged device contains the following important information: (1) device IDs from its one-hop neighbors including the tagged device; (2) MN of the minislot occupied by the tagged device; (3) buffer occupancy bit (BO), BO = 1 if the device's transmission buffer is non-empty and 0 otherwise; and (4) previous DN, indicating the DN of the occupied data slot from the tagged device in previous superframe, with DN = 0 if the device was not allocated a data slot in the previous superframe. The selection of one minislot from the tagged device is considered successful if the broadcast control packets at subsequent minislots following the selected minislot contain the tagged device ID, and thus the same minislot will be selected in every subsequent superframe. Otherwise, collision happens for accessing the minislot, and all the devices involved will wait until the next superframe for a new minislot selection. With the consideration of the *on/off* traffic statistics, only active voice devices (i.e., the devices with BO = 1 in broadcast control packets) are allocated data transmission time slots after accessing the minislots, to adapt to instantaneous voice traffic load. Two categories of active voice devices are defined: category I and category II. A category I device is currently active but was not allocated a data slot in previous superframe, whereas a category II device is active in both current and previous superframes. Since the activation of category I device is at some



Adaptive Medium Access Control for Internet-of-Things-Enabled MANETs, Fig. 2 A hybrid MAC superframe structure random time instant before its minislot accessing time at current superframe, category I devices are prioritized over category II devices for the time slot scheduling. Specifically, category I devices are scheduled data time slots first by following their minislot accessing sequence to minimize the packet delay bound violation probability, under the condition that each category II device can be scheduled a time slot no later than the same time slot as in previous superframe.

After the TDMA period, the data devices contend for the channel access by employing the T-CSMA/CA scheme. The T-CSMA/CA is similar as the CSMA/CA with exponential backoff, except that the contention-based packet transmissions in one superframe are periodically interrupted by the presence of its subsequent superframe. Therefore, the performance of T-CSMA/CA is different from the CSMA/CA in the following two aspects: (1) the packet waiting time before transmission is enlarged by the control period and the TDMA period of each superframe; and (2) before transmitting one packet at the end of the exponential backoff phase, each device needs to check whether the remaining time in current superframe is enough to transmit at least one packet. If the remaining time is less than the summation of a complete packet transmission time (T_{pk}) and a guard time (T_{gt}), a virtual conflict occurs and ($T_{pk} + T_{gt}$) is the duration of the conflict period, as shown in Fig. 3. Then, all devices involved in a virtual conflict are required to hold on the packet transmissions until the beginning of subsequent T-CSMA/CA period.

The optimal parameters of the proposed hybrid MAC solution are derived, which are adaptive to varying numbers of voice and data devices to achieve bounded voice packet delay and consistently maximum data throughput. For the delay-sensitive voice service, given the maximum fraction of channel time, ρ, allocated to voice traffic in each superframe, the voice capacity N_{mi} supported in the network is analyzed, which is also the number of minislots configured for the control period of each superframe, to guarantee the voice packet loss rate bounded by P_l. Given N_v, the maximum number of voice bursts (data slots), denoted by N_{sm}, that can be scheduled in each superframe to achieve P_l is then determined. Since the actual number of scheduled data slots in each superframe is likely less than N_{sm}, the average number of scheduled data slots $\overline{N_{sv}}$ and the average duration $\overline{T_d}$ of each TDMA period are also calculated. Moreover, N_{sm}, $\overline{N_{sv}}$, and $\overline{T_d}$ are dynamically adapted to the variation of N_v to achieve a consistently bounded voice packet loss rate. After obtaining T_c and $\overline{T_d}$, the average duration $\overline{T_s}$ of the T-CSMA/CA period is also determined, which is employed for channel access by N_d data devices. Therefore, the aggregate data throughput S_d in the T-CSMA/CA period of each superframe is further derived in terms of N_v, N_d, and the packet transmission probability τ_d from each device at a backoff slot. After some algebraic manipulation and certain approximation, the optimal transmission probability τ_d^{opt} and the corresponding optimal contention window size CW^{opt} to achieve maximum aggregate data



Adaptive Medium Access Control for Internet-of-Things-Enabled MANETs, Fig. 3 An illustration of T-CSMA/CA period in each superframe throughput $S_d^{\max}$ are obtained in closed-form expressions of N_v and N_d. With the derived performance analytical models, the optimal MAC parameters CW^{opt} and τ_d^{opt} can also be dynamically adjusted with variations of N_v and N_d. Therefore, the proposed hybrid MAC solution in supporting heterogeneous services optimizes the MAC configurations and adapts the optimal MAC parameters to heterogeneous traffic load conditions for maintaining consistently maximum network performance.

Our proposed adaptive MAC solutions for both homogeneous and heterogeneous service scenarios are useful in an IoT-based network environment, where conventional cellular communication infrastructures are inaccessible and devices are interacted via an ad hoc networking. For example, in a postdisaster area, a large number of smartphones and smart sensors are required to be interconnected for information dissemination. The proposed MAC solutions are efficient in coordinating channel access from the smart devices in an infrastructure-less manner and adapting the MAC performance to the network load fluctuations due to device activation/deactivation and device mobility.

Numerical Results

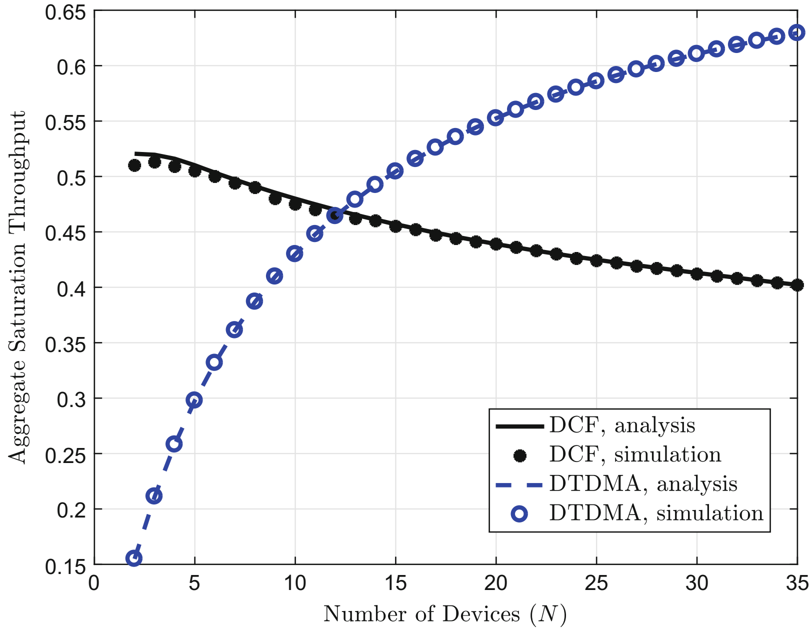
Simulation results are provided to verify the effectiveness of the proposed adaptive MAC solutions. All simulations are carried out by using the network simulator OMNeT++. In the simulation, devices are randomly scattered over a $100 \times 100\,\text{m}$ square region and are within one-hop communication ranges of other devices. Each source device randomly selects its destination among the other devices. For the homogeneous service scenario, devices are with the same type of high-rate data application. Packet arrivals at each data device are assumed to follow a Poisson process with the average packet arrival rate set as 300 packet/s for the traffic saturation state (results for a traffic non-saturation state are provided in Ye et al. 2016). For the heterogeneous service scenario, there are a mixture of delay-sensitive voice devices and high-rate data devices in the network. Voice traffic is generated periodically during the *on* state with the rate of 50 packet/s. Other system parameters for the simulation are provided in Ye et al. (2016) and Ye and Zhuang (2017b).

Performance comparison between DCF and DTDMA is conducted for the homogeneous service scenario. Figure 4 shows the aggregate saturation throughput for both candidate MAC protocols with the variation of N. It can be seen that the optimal MAC switching threshold, N^*, exists at the network load point when the two MAC candidates achieve the same throughput. Based on the derived closed-form performance analytical models, the optimal MAC switching threshold can be determined in a distributed way with low complexity, upon which the adaptive MAC solution achieves consistently maximum network throughput.

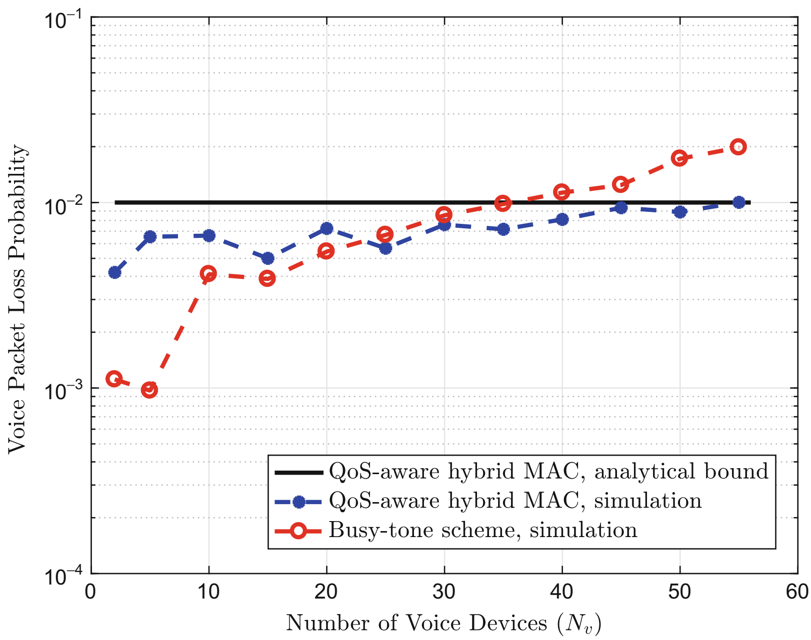
For the proposed QoS-aware hybrid MAC solution, the voice packet loss rate is evaluated in Fig. 5. It is verified through simulations that the proposed distributed and adaptive time slot allocation mechanism always guarantees a packet loss rate below the analytical bound as long as the number of admitted voice devices is within the voice capacity. Although the busy tone-based MAC scheme (Wang et al. 2007) achieves a bounded packet delay in a low network load condition, the transmission collisions among voice devices are accumulated as the network load increases, leading to degraded service performance. The average T-CSMA/CA channel utilization within each hybrid MAC superframe is shown in Fig. 6, which is defined as the ratio of average time for successful data transmissions inside a T-CSMA/CA period over the length of the T-CSMA/CA period. Since MAC parameters are optimized for the T-CSMA/CA, the channel utilization is consistently maximum with respect to a varying N_d.

Conclusion

In this entry, the backgrounds of distributed and adaptive MAC schemes for an IoT-enabled MANET are investigated. Novel adaptive MAC solutions are presented for both homogeneous and heterogeneous service scenarios. For the homogeneous service scenario, a hybrid MAC scheme is proposed to switch between the IEEE

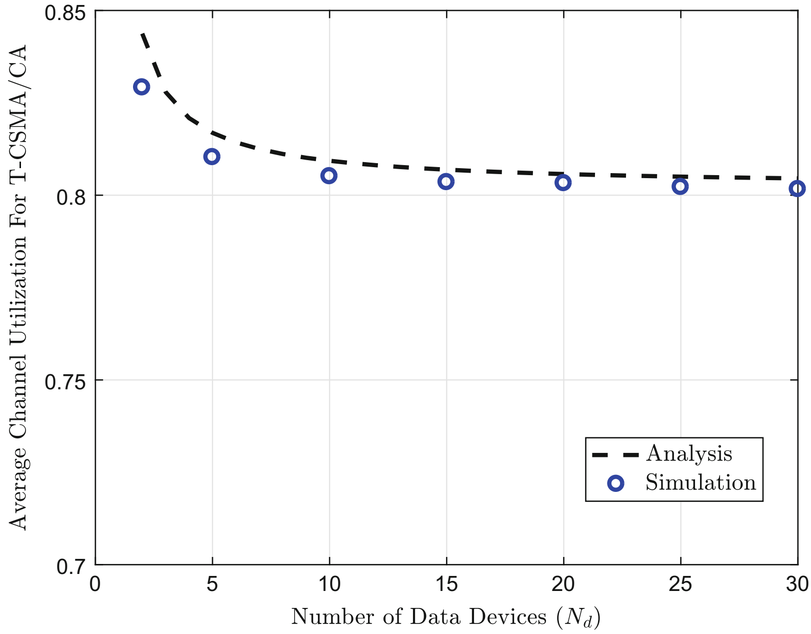


Adaptive Medium Access Control for Internet-of-Things-Enabled MANETs, Fig. 4 Throughput comparison between DCF and DTDMA



Adaptive Medium Access Control for Internet-of-Things-Enabled MANETs, Fig. 5 Voice packet loss rate ($N_d = 10$, $\rho = 0.5$)

802.11 DCF and the DTDMA according to the network load conditions. Based on the throughput analysis of both MAC candidates, an optimal MAC switching threshold is derived in terms



Adaptive Medium Access Control for Internet-of-Things-Enabled MANETs, Fig. 6 Average channel utilization of T-CSMA/CA in each superframe ($N_v = 20$, $\rho = 0.5$)

of the number of devices in the network. For the heterogeneous service scenario, a QoS-aware hybrid MAC scheme is presented to differentiate the channel access for voice and data devices, where adaptive time slot allocation is conducted for voice traffic and a T-CSMA/CA scheme is employed for data traffic. The MAC parameters of the proposed scheme are optimized and are adaptive to the heterogeneous network traffic load, to achieve bound voice packet delay and consistently maximum aggregate data throughput. Simulation results are presented to verify the advantages of the proposed schemes. The applications of the adaptive MAC solutions are also discussed.

Cross-References

- ▶ Media Access Control for Narrow Band Internet of Things, Survey
- ▶ Multiple Access Techniques
- ▶ QoS-Aware MAC
- ▶ Quality of Service in IEEE 802.11 Networks

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