Fine Time Measurement based Time Synchronization for Multi-AP Wireless Industrial Environments

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***Abstract*—In Industrial environments, such as factories, equipment are often connected through Ethernet or its complementary Time Sensitive Networking to support critical applications that require low latency and low jitter in the order of milliseconds. To meet these requirements, precise time synchronization across all wired devices is typically achieved using the Precision Time Protocol (PTP) at the Local Area Network (LAN) level. Although PTP can synchronize devices across wireless networks, Wi-Fi has more effective synchronization mechanisms, like Fine Time Measurement (FTM) that can achieve precise and tight synchronization. As new wireless standards like Wi-Fi 6/7 are integrated into industrial networks, the number of wireless devices in these networks is increasing. It is essential to consider new functionalities, such as multi access point (AP) coordination, which require precise time synchronization. Aiming at contributing to the time synchronization solution across multi-AP industrial internet of things (IIoT) environments, this paper proposes an approach based on multi-level hierarchical methodology to synchronize the devices. It provides a method for selecting the best FTM Responder to distribute time when multiple FTM responders and initiators are present in the network. The evaluation of the proposed methodologies indicates that it successfully synchronizes all devices within the network, and the best FTM responder selection algorithm performs as expected.**

***Index Terms*—Time Synchronization, IIoT, multi-AP, Fine Time Measurement**

I. Introduction

Industrial IoT (IIoT) is used in manufacturing environments to automate processes and increase efficiency while decreasing the need for human intervention. To achieve this, robots, sensors, actuators, and IoT platforms are interconnected through various networking technologies, such as Ethernet and Time-Sensitive Networking (TSN), which provide reliable packet transmission, low jitter, bounded latency, and zero congestion control [1]. Time synchronization in wired networks is currently well supported by IEEE 1588 at a *Local Area Network (LAN)* level *Precision Time Protocol* (PTP), with an accuracy of nanoseconds [2]. However, as manufacturing environments evolve, different wireless technologies are being applied due to their flexibility and lower deployment cost, allowing for the deployment of new services like mobile robots. The 802.11 working group has introduced new amendments to Wi-Fi, specifically 802.11ax and 802.11be, to support TSN capabilities and offer low-latency and ultra-reliability. Tight time synchronization is a requirement in TSN, which becomes challenging in wireless networks due to complex scenarios, asymmetric delays, and mobile devices. Efforts have been made to extend TSN support to wireless networks, including addressing multiple aspects, such as time synchronization adapted to wireless [3], particularly in multi access point (AP) environments. Achieving deterministic support in wireless environments is crucial, as different wireless industrial scenarios, such as those in manufacturing, aeronautics, and transportation, present additional challenges for time synchronization [4].

This work aims to explore Fine Timing Measurement (FTM) in multi-AP environments to improve adaptability to wireless medium and support real-time and critical applications in industrial environments. The research involves designing and evaluating novel FTM extensions for multi-AP environments, investigating the feasibility of APs initiating the FTM time synchronization process, and proposing a procedure for selecting the best FTM responder for an overlapping Basic Service Set (BSS) environment. The study will use ns-3 modules to support time synchronization between wireless devices while maintaining backward compatibility with IEEE 1588. The research will evaluate different scenarios, considering factors such as the number of APs and wireless stations (STAs), mobile and static devices, propagation delay models, and channel parameters.

The rest of the paper is organized as follows. Section II gives background and related work analysis. Section III explains the hierarchical approach for synchronization. Section IV describes the methodology for selection of best FTM responder. Section V gives insights to implementation aspects. Section VI describes the performance evaluation carried out and the results achieved on a ns-3 simulation framework. Lastly, Section VII concludes the paper.

II. Background and Related Work

This section provides an basics of FTM, synchronization mechanism based on FTM, and an overview of time synchronization mechanisms in the context of multi-point networks.

A. Fine Time Measurement

The Wi-Fi FTM is a MAC layer protocol which is currently specified for time-of-flight positioning, in its original form in the IEEE 802.11mc (IEEE 802.11-2016) [5], to facilitate localization. The protocol enables a node to determine its distance from another node/AP with high accuracy in the order of meters. FTM computes relative distance via the measurement of time-of-flight between an initiator node and a responder node. In comparison to signal strength propagation loss approaches, by relying on the time-of-flight, FTM is linearly dependent on the range. Figure 1 illustrates the FTM communication sequence. In our scheme, the initiator is STA, which starts by sending an FTM request to AP (Responder). Based on the answer of the AP which could be either Acknowledgement (ACK) or no ACK, FTM will continue the process. If an ACK is sent by the AP acknowledging the FTM request, then the AP sends an FTM message (FTM1). This process may then be repeated provided that the ACKs are adequately received by the responder.

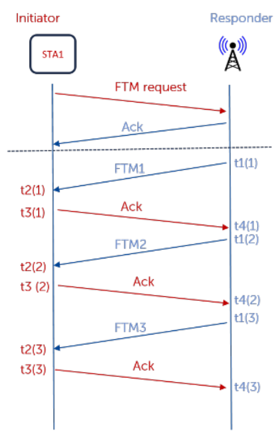


Fig. 1. FTM communication sequence for RTT computation.

The FTM computation of the RTT for n FTM messages is provided in equation below

$$RTT = \frac{1}{n}(\sum_{k=1}^{n} t4(k) - \sum_{k=1}^{n} t1(k)) - \frac{1}{n}(\sum_{k=1}^{n} t3(k) - \sum_{k=1}^{n} t2(k)) \quad (1)$$

It should be highlighted that FTM requires repeated measurement, as the RTT measurements are not completely accurate, depending on aspects such as: RF interference, position of stations towards APs, whether the measurement is performed in LoS or nLoS. Relevant to highlight is the integration of FTM into 802.1AS-Rev and also its achievable picosecond resolution. An additional advantage of FTM is that it can be used from AP to STA or between STAs/APs, thus introducing flexibility to bring synchronization to multi-AP scenarios.

B. FTM based Time Synchronization

While there were no prior implementations of FTM based time synchronization, Sugandh et al. [6] conducted research on time synchronization using the FTM protocol on Linux open MAC devices and Wi-Fi6 NICs within the context of the fortiss TSNWiFi [7] project. The authors aimed to create a time synchronization solution compatible with IEEE 1588 profile for PTP. They found that Linux open MAC drivers were not as open as expected and implemented a proof-of-concept using Beacon frames but did not use action frames. Later, they extended their work [8] by implementing the solution on an ns-3 simulator and evaluating it on a deterministic wireless/wired framework. Results showed FTM as a promising candidate for providing accurate backward compatible synchronization to IEEE 1588/PTP. However, a few challenges remain, such as understanding the impact of distance variations on synchronization and identifying which FTM parameters can achieve higher synchronization resolution.

C. Time Synchronization in Wireless Multi-Point Environments

While time synchronization in wireless networks is a widely studied topic, the majority of research on time synchronization in multi-point/multi-AP wireless networks specifically comes from the field of Wireless Sensor Networks (WSN).

Jia et al. [9] propose a distributed clock synchronization protocol for multi-AP networks using a 2-phase synchronization proposal that clusters nodes based on varying skew rates to synchronize nodes more frequently. A fault detection algorithm is integrated to improve synchronization security. The proposal lacks clarity on worst-case synchronization error, but it may be valuable for networks exceeding 150 nodes.

Jie et al. [10] propose a hybrid approach called Clustered Consensus Time Synchronization (CCTS) that incorporates Distributed Consensus Time Synchronization techniques to improve convergence speed and energy efficiency. The CCTS algorithm is divided into intra-cluster and inter-cluster time synchronization, with cluster heads being responsible for exchanging messages within the cluster and updating the clock compensation parameters. However, the work does not consider node failures or message loss.

Zurani et al. [11] propose a Clustered Time Synchronization (CTS) algorithm that uses a top-down tree-based architectural design for creating multi-level clusters. The CTS algorithm is composed of two phases, and it uses a pairwise packet exchange mechanism and a reference broadcast mechanism to synchronize time between the base station, cluster heads, and cluster members. The algorithm shows improved synchronization accuracy, lower power consumption, and better synchronization precision when compared to other algorithms, but it emphasizes more on energy consumption.

Yong et al. [12] propose a two-step time synchronization algorithm for sensor networks that reduces energy consumption and accurately estimates clock drift and offset for high-precision performance. The algorithm builds a spanning tree in the sensor network and synchronizes all node's clocks to their parent nodes. The algorithm shows improved synchronization accuracy compared to other algorithms, but some do not take into account node failures or message loss.

III. Multi-Level Hierarchical Approach

After examining various architectural designs for synchronizing devices in multi-point wireless networks, we propose a method for synchronizing devices in IIoT wireless environments. Figure 2 illustrates an example of IIoT wireless environment that contain multiple APs and STAs. It can be seen from the figure that there are multiple APs with overlapping BSSs.

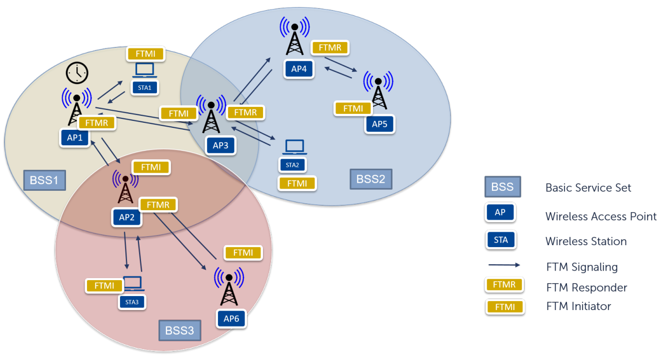


Fig. 2. Example of a multi-AP IIoT environment.

The proposed approach takes into account three considerations to facilitate synchronization in large-scale IIoT networks: the FTM responder distributes time to FTM initiators, a designated master AP holds the master clock and distributes time, and APs can act as both FTM responders and initiators.

The process of synchronizing devices across multiple levels using the FTM protocol involves a designated master AP broadcasting its capability to distribute time via Management frames, which are currently using Beacon frames. The APs and STAs within the radio range of the master AP receive the Beacon frames and can synchronize to the master AP by initiating an FTM request. Devices that have been synchronized in the first level are given the opportunity to synchronize devices in their BSS by announcing their capability to act as FTM responder in their respective Beacons. This process continues until all the APs and STAs in the network are synchronized, and it can be repeated as long as required. Figure 3 represents two levels of operation.

Regarding the FTM synchronization process, the following steps are involved: first, an FTM request is triggered when an AP or STA receives information about a potential FTM responder in a parsed Beacon frame. The FTM responder validates the FTM parameters and sends an ACK if they are acceptable, then sends a burst of FTM frames specified in the FTM request. The first FTM frame does not include timestamps from previous FTMs, while subsequent FTM frames include timestamps from previous FTMs. The initiator device can now correct its offset to the responding AP once it receives the second FTM frame. Once the last FTM frame of the burst is received, the initiator AP or STA can calculate the propagation delay and is now both offset and delay compensated. This process is repeated for subsequent bursts, and the use of multiple bursts improves the accuracy of the measurements.

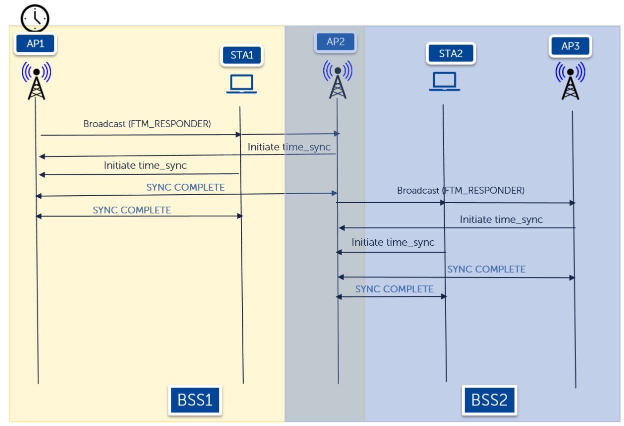


Fig. 3. Hierarchical Approach - Level 2

IV. Selection of FTM Responder

In a network with multiple APs or FTM responders within range of a STA as depicted in Figure 4 , it is crucial to choose the optimal AP to send an FTM request for better time accuracy, taking into account factors such as channel bandwidth, link quality, LoS/nLoS, etc.

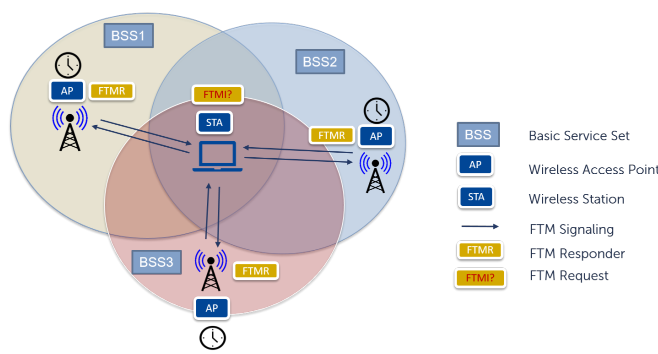


Fig. 4. A STA with multiple FTM Responders

To address this issue, we are considering the studies that have been conducted to determine the optimal access point for association. Some of the proposed methods include throughput estimation based on frame timing and interference, MAC layer bandwidth estimation based on Beacon delays, and RSSI and interference estimation using frame re-transmission [13], [14], [15] and [16].

We incorporate some of the ideas mentioned above to the context of selecting a best FTM responder, also considering the accuracy of the timing measurements of FTM. To decide which AP to send a FTM request to, there are several factors to consider. Firstly, the location of the AP can impact the signal strength and quality of the connection between the STA and AP. Secondly, it is important to select an AP with the highest supported rates since APs with higher data rates have the capability to handle a greater number of users, allowing them to efficiently manage a larger number of connected devices. This approach is similar to [17]. Thirdly, channel width should be considered as a wider channel generally provides a higher throughput, and [18] argues that the accuracy of the FTM ranging increases with channel width. Fourthly, increasing the number of FTM frames per burst enhances the granularity of FTM measurements [19]. Additionally, the number of STAs being served and the number of FTM requests being served should be taken into account. When an access point is serving a large number of STAs, it may result in higher congestion and interference on the channel. The assignment of the FTM responder should be made with the aim of evenly distributing the FTM requests, so as to prevent one AP or FTM responder from handling all the requests.

The above factors provide metrics which are Min-Max normalized [20] between zero and one. Then, each metric has been given an equal weight to calculate a score that select the best FTM responder.

V. Implementation Aspects

Based on a prior work by Sugandh et al. [6] and as explained in the Section II-B, it has been determined that Linux open MAC drivers are not as open as claimed, thus making it infeasible to implement proposed time synchronization solutions. Due to this limitation, we have chosen ns-3 simulator to implement the proposed methodologies. The ns-3 DetNetWiFi Framework [21] serves as the foundation for all of the implementations. The necessary modules like ns3-FTM is borrowed from TU Berlin [22] and clock model from [23]. The explanations and usage of each required modules is well documented in their respective sources. The code and its usage pertaining to the implementation of hierarchical approach and selection of best FTM responder is accessible in [21].

VI. Performance Evaluation

This section presents the performance evaluation of the developed methodologies described in previous sections.

A. Evaluation - Hierarchical approach

This section describes the evaluation of a multi-level hierarchical approach for synchronization accuracy between an AP (FTM Responder) and an STA (FTM Initiator), and the total network synchronization time. The experiments were conducted using the 802.11ax Wi-Fi standard operating at 5 GHz with an 80 MHz channel width. The experiments were carried out in several scenarios, including a control scenario and variable scenarios where parameters such as the number of nodes and distances were varied. Two propagation models, the Friis Propagation Model [24] and the Hybrid Building Propagation Model [25], were used to predict wireless signal behavior. The FTM protocol parameters used in the experiments were four bursts with three FTMs each, and the minimum delta was set to 100s. Next we see the performance for different scenarios for which the experiments are conducted five times for each scenario, and the resulting performance parameters are averaged. Figure 5 depicts an example measurement setup.

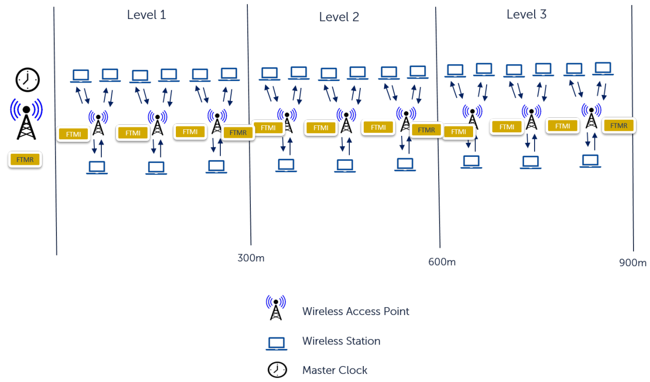
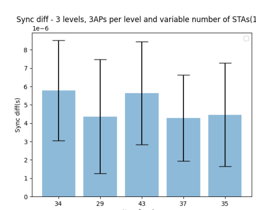
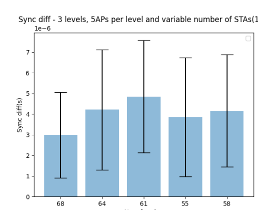


Fig. 5. Measurement Setup Topology - 3 levels, 3 APs per levels and 3 STAs per AP.

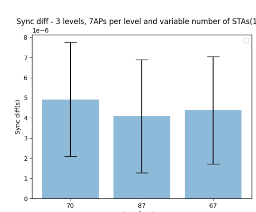
1) Variable Number of STAs and APs, and Variable Distances: This scenario evaluates the impact of the number of STAs per AP. It consists of three configurations, each with three levels of operation, and 3, 5, or 7 APs per level, with a variable number of STAs randomly selected from 1 to 5. The distances between APs are also varied. The objective is to study how performance parameters change with the number of STAs. The distances were chosen to ensure that the necessary number of APs are still within 1 level to test performance impact. Plot (a), (b) and (c) of Figure 6 displays the synchronization difference between the FTM responder and FTM initiators for various numbers of nodes. Plot (d) shows the total synchronization time. The results show that increasing the number of APs increases network size and affects performance, as APs generate Beacons once they are synchronized. However, the network density has no impact on total synchronization time.



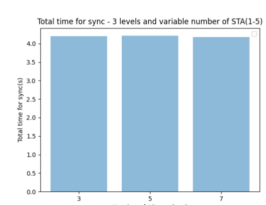
(a) Synchronization difference



(b) Total time for synchronization



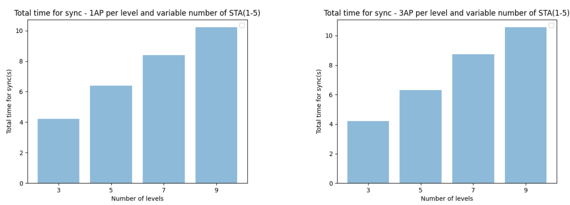
(c) Total time for synchronization



(d) Total time for synchronization

Fig. 6. 1 - Synchronization difference and Total Time for Synchronization.

2) Variable Number of STAs, Static Number of APs per Level, and Variable Number of Levels: This scenario studies the effect of changes in operational levels on the network synchronization time. The number of STAs per AP ranges from 1 to 5, with 1 AP per level and operational levels varying from 5 to 9. The distance between APs is set to 300m. Three sub-scenarios are presented with varying operational levels and numbers of STAs per level. The results depicted in Figure 7 show that the total synchronization time increases with the number of operational levels, but the number of APs per level has no significant impact on synchronization time. The synchronization difference performed similarly to previous scenarios.



(a) Total Time for Synchronization - 1 AP (b) Total Time for Synchronization - 3 APs

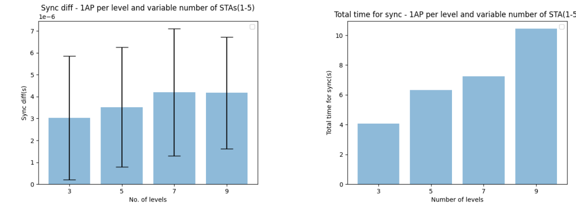
Fig. 7. 2 - Total Time for Synchronization.

3) Mobile STAs and Impact Assessment of Various Propagation Models: For the Mobile STAs scenario, the impact of mobility on synchronization performance was explored through a constant velocity model with a speed of 2m/s. The levels of operation were tested at 5, 7, and 9, each having 3 APs, and the number of levels of operation had a greater impact on performance than the number of APs per level. The results showed little to no effect from a speed of 2m/s, but a speed of 20m/s was considered unrealistic and unsuitable for the setup as it would cause the device to quickly exceed its range limits.

The next scenario was executed to asses the impact of switching from FriisPropagation to HybridBuildingPropagation, which better represents the features of an industrial/manufacturing/factory setup. The setup initially led to greater path loss than with the Friis-Propagation model, and the distance between levels was kept under 100 meters to avoid out-of-range conditions. Increasing the number of APs per level had no impact on the total synchronization time, and the range of any AP was limited to less than 100m. Overall, the results of these scenarios are depicted in Figure 8 provide insight into the impact of mobility and propagation models on synchronization performance in IIoT environments.

B. Evaluation - Selection of best FTM responder

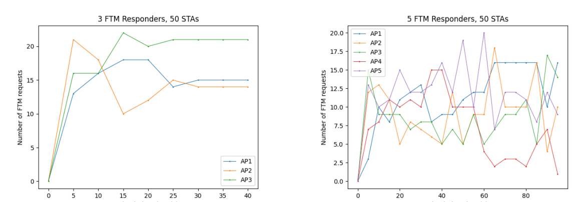
In this section, the performance of an algorithm for selecting the best FTM responder is evaluated. The evaluation considered various factors with equal weightage to prevent overloading, and simulation results provide insight into the FTM responder selection process. To conduct the evaluation, 50 STAs were randomly placed within a 100 m x 100 m area served by 3 or 5 APs, resulting in two sub-scenarios. The availability of 3 or 5 FTM responders was considered, and the



(a) Synchronization difference. (b) Total Time for synchronization

Fig. 8. 3 - Synchronization difference and Total Time for Synchronization

Hybrid Buildings Propagation model was used as the propagation model. All STAs moved at a constant speed of 2m/s. For Algorithm Validation experiments, the STAs generated a FTM request every 5s, and the number of connected STAs to each AP was randomly selected from a uniform distribution. STAs determined the supported rates and the number of FTMs supported from the AP's Beacons, operating on an 80MHz channel. The experiments aimed to observe the distribution of FTM requests among FTM responders to ensure even distribution, with factors outlined in the architectural description. The achieved results were plotted in Figure 9 in terms of FTM requests received per AP over the simulation period for 3 and 5 FTM responders. The proposed algorithm facilitated better FTM responder selection and prevented overcrowding of any one AP, achieving improved load balancing in FTM request management across available responders.

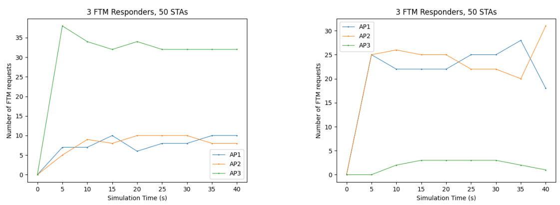


(a) Number of Responders - 3. (b) Number of Responders - 5

Fig. 9. Validation of the Selection of best FTM responder algorithm - Number of FTM requests received per AP.

We investigated FTM Requests Load balancing capability by considering the following scenario involving 3 APs. In Figure 10, AP3 was not serving any active STAs, and then its load was changed to serve 40 STAs. The aim was to understand how the algorithm assists in providing better load balancing in terms of FTM requests. The plot (a) shows the situation when AP3 has no active STAs associated and plot (b) showing the situation when AP3 is serving 40 active STAs. Results show that the algorithm assists in better load balancing of FTM requests, selecting AP3 as the best responder, and thus, AP2 and AP1 serve a similar level of requests. When AP3 handles 40 active STAs, the algorithm assists in diverting the FTM requests to AP1 and AP2.

Overall, the evaluation shows that the proposed algorithm provides better load balancing in FTM request management across available responders.



(a) Number of Responders - 3.

(b) Number of Responders - 3

Fig. 10. Variation of number of Associated STAs

VII. Conclusion

This research aimed to develop a methodology for accurately synchronizing devices in a multi-AP industrial environment. The proposed multi-level hierarchical approach for synchronization and algorithm for selecting the optimal FTM responder were evaluated using the ns-3 simulator under different network conditions. Results showed that the number of levels of operation had a greater impact on total synchronization time than the network density, and the algorithm for selecting the best FTM responder was found to be effective in distributing requests without overburdening individual responders. Future work includes scaling methods, optimizing computational efficiency, exploring alternative time synchronization methods, and investigating techniques for dynamic synchronization adaptation.

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